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A SPACELAB MICROGRAVITY EXPERIMENT

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SUMMARY

The surface tension driven convection experiment (STDCE) is a Space Transportation System flight experiment manifested to fly aboard the USML-1 Spacelab mission planned for March 1992. A CO₂ laser is used to heat a spot on the surface of silicone oil contained inside a test chamber. Several CO₂ laser control systems have been evaluated and the selected system will be interfaced with the balance of the experimental hardware to constitute a working engineering model. Descriptions and a discussion of these various design approaches are the subjects of this report.

INTRODUCTION

The science requirements of the STDCE call for the power output of the CO₂ laser to be set at three different levels: 3.0, 0.5, and 0.2 W. Additional science requirements call for the laser output power to be stable in time to within ± 5 percent and to be within ± 10 percent of the setpoint at all times with the exception of a specified warmup time. The modal stability and output power level of a CO₂ laser are dependent upon its thermal stability. A common method of stabilizing the output power of a CO₂ laser is to accurately control the length of the laser cavity by controlling the temperature of the laser tube. The temperature of the laser tube for STDCE must be within a few hundredths of 1 °C to meet the science requirements. The thermal control systems on board the Spacelab are not capable of providing such temperature stability.

Efforts to find a commercially available laser system with the required range of power adjustment and stability were fruitless. Therefore, the development of a closed-loop electronic laser power control system was begun.

Two basic approaches to controlling laser power were considered:

- (1) Variable duty cycle pulse-width modulation (PWM) with constant beam intensity
- (2) Variable beam intensity with continuous wave power

Both of these approaches were implemented in two different ways: one under the direct control of a microprocessor and the other with an analog or other non-digital control system. In all, four combinations were tested:

- (1) PWM - microprocessor based
- (2) PWM - analog
- (3) Variable beam intensity - microprocessor based
- (4) Variable beam intensity - analog

This report describes the hardware and/or software of each of these approaches and discusses the results observed in laboratory tests. Also included in the discussion are some of the pros and cons of each approach with regard to their impact on experimental equipment and compatibility with Space-lab facilities and requirements. The concluding discussion presents the reasons for selecting the analog variable intensity closed-loop control system along with some of the compromises which were accepted.

The laser used for these tests was an RF-excited CO₂ laser. The results reported here apply specifically to this laser. Lasers of other designs, such as high-voltage excited or nonwaveguide, may not be adaptable to the methods of control described in this report.

The information and experience reported here should be beneficial to future microgravity experiment developers who may have a need to control or stabilize the power of a CO₂ laser, whether it is on the Spacelab or Space Station. In addition to space experiment applications, there may be some benefit for ground-based systems by providing electronic laser power stabilization.

SURFACE HEATING SYSTEM

The configuration of the hardware necessary to implement the surface heating system is shown in figure 1. The components include the CO₂ laser, the optical system, the power meter, the test chamber, the silicone oil, and the closed-loop controller.

CO₂ LASER

A CO₂ laser was selected to heat the silicone oil because it produces radiation at a wavelength (10.6 μm) which silicone oil readily absorbs. The laser selected was a Laakmann Electro-Optics Incorporated model number RF-88 RF excited laser with a rated output of 7 W. It is powered by a Laakmann Electro-Optics model number RF-100-40, 40 MHz RF power supply. The required power source is 28 V dc (± 4 V).

This particular laser was selected because the power requirement is compatible with the power source of the Spacelab, and because of its physically rugged waveguide design. Thus, it is a possible candidate for adaptability to flight hardware.

The laser is mounted on a water-cooled base plate to remove waste heat by means of conduction. The open-loop characteristics of the laser are indicated in figure 2. The power output is within ± 7 percent of the setpoint, which exceeds the ± 5 percent level permitted by the science requirements.

In addition, factors such as power meter and optical system calibration accuracies affect the ability to determine the absolute power being delivered to the oil surface. The CO₂ laser is shown in figure 3.

OPTICAL SYSTEM

Figure 4 is a diagram showing the main components of the laser optical system. The beam splitter functions both as a turning mirror and a sampling window for the power meter. The final optical design uses three separate beam splitters which are interchanged according to the power setpoint. The beam splitters have been calibrated to an accuracy of ± 1 percent by the manufacturer. In addition, they have a variation in reflectance of about $\pm 1\frac{1}{2}$ percent over the wavelength range of a CO₂ laser.

Table I shows the beam splitting ratios used in the final design, along with the corresponding power levels of the laser beam components entering and leaving the beam splitter. There are several advantages in using multiple beam splitting ratios.

- (1) They provide coarse power range selection.
- (2) They provide a high signal for the power meter at all power levels, thus providing a good signal-to-noise ratio for the controller.
- (3) The laser can be operated at nearly the same power level for all three setpoints, thus allowing the controller to function essentially as a power stabilizer rather than as a broad range power selector.

POWER METER

A Coherent model 210 thermopile power meter is used to sense the portion of the laser radiation coming through the beam splitter. The meter produces an output of 2 mV/W ± 3 percent and has a response time of less than 1 sec. The output voltage from the power meter is used as a feedback signal for the closed-loop control system as well as a power output monitor for the CO₂ laser. The power meter is cooled by ambient air and is rated at 10 W. Because the highest power level seen by the meter is only a little over 3 W, the power meter should serve adequately despite derating for the absence of natural convection at zero gravity. The power meter is shown in figure 5.

TEST CHAMBER

The test chamber is a cylindrical container 10 cm in diameter and 5 cm in height (fig. 6). To ensure good thermal boundary conditions at the side wall, it is made of copper.

SILICONE OIL

Silicone oil was selected as the test fluid primarily because its viscosity represents the best compromise between flow speed and susceptibility to free surface disturbances. It is also safe and insensitive to surface contamination, which is a common problem with surface tension experiments.

CLOSED-LOOP CONTROLLER

The closed-loop controller can be either analog or digital in nature. Both types of controllers were evaluated in conjunction with pulse-width modulation (PWM) and variable beam intensity control of the laser. A closed-loop controller regulates a final control element in response to the setpoint and process variable input signals to maintain the process variable at the selected setpoint. A three-mode controller was used for this application.

A three-mode controller provides three control functions: proportional action, reset (integral) action, and rate (derivative) action. Proportional action causes the output to change in proportion to a change in the magnitude of the deviation. Reset action adds a component to the controller response proportional to the time integral of the deviation. Rate action adds a component to the controller response proportional to the rate of change (derivative) of the deviation. When a change in process conditions causes a change in the process variable, a controller with proportional action alone requires some magnitude of deviation for corrective action, leaving an offset between the actual and desired value of the process variable. Reset action provides continuing correction until the deviation and offset are virtually eliminated. Rate action provides corrective action based on the rate of change of the deviation. This tends to improve loop stability, allowing more favorable proportional band and reset settings. Rate also increases the initial correction speed and reduces the time required for the process to return to the setpoint.

ANALOG CLOSED-LOOP CONTROLLER

A commercial three-mode controller was used for evaluating the effectiveness of an analog controller for this application. A block diagram of the analog controller is shown in figure 7. The deviation amplifier receives a process variable signal and a setpoint signal. The amplifier compares the two signals and produces a signal equal to the difference between those signals. The polarity of the deviation depends upon which input is larger. The deviation amplifier output signal is inverted in the mode amplifier and converted into controller outputs in the current driver. The proportional band and rate settings control the mode amplifier response to the deviation signal. The reset setting controls the rate at which an unchanging deviation signal changes the output of the mode amplifier.

DIGITAL CLOSED-LOOP CONTROLLER

The STDCE utilizes an onboard experiment computer for data acquisition and control. It is an STD bus system which is a card-based microprocessor system standardized physically and electrically, permitting any STD card to be plugged into any bus slot. The controller used for evaluating digital control of the CO₂ laser implemented the STD bus. Two different systems were required to provide PWM and variable beam intensity control. The two are identical in all respects except for the output driver software and hardware. A block diagram of the digital controller is shown in figure 8 and the software flowchart is shown in figure 9.

The software consists of three major modules. These modules are the initialization, warmup, and PID modules. The initialization module provides an operator interface. The operator enters the operational parameters of the control system that consists of setpoint, deadband, maximum laser output power, sensor calibration constant, proportional gain, integral gain, derivative gain, and update rate. The warmup module uses the operational parameters to compute an initial (open-loop) output. A 4-sec warmup period is provided to permit the output to stabilize prior to initiating closed-loop control. The PID module uses the operational parameters to complete the closed-loop control output. Figure 10 illustrates the PID algorithm. The operator is permitted to enter a new setpoint and time delay at this time. A detailed description of the digital controller, including the software listing, is included in appendix A.

CO₂ LASER CONTROL SYSTEM TEST CONFIGURATIONS

CO₂ Laser Pulse-Width Modulation (PWM) Control

The output power of the laser can be controlled by pulse-width modulation of the RF power supply. Figure 11 shows an open-loop plot of the laser output power as a function of pulse width at a fixed repetition rate of 1 kHz for a thermally stable laser system. The laser output is almost linear down to approximately 0.1 W and then rapidly decreases to zero. The laser characteristics also change with age and temperature. The PWM signal required for control of the RF power supply is an open collector, capable of handling a minimum of 28 V, with a fixed repetition rate of 1 kHz and a pulse-width variable from 50 μ sec to 1 msec with a resolution of 10 μ sec for this application.

CO₂ Laser Digital Pulse-Width Modulation (PWM) Closed-Loop Control System

A digital PWM closed-loop control system for the laser was configured with the digital controller previously described and a digital PWM card. A block diagram of the system is shown in figure 12. A block diagram of the digital PWM card is shown in figure 13.

The 5-MHz clock signal from the STD bus is converted to a 1-MHz signal by a divide-by-five circuit. The 1-MHz signal is taken to a three-stage binary divider by means of a clock synchronizer. The divider is programmed from the STD bus to permit frequency division to be programmed from 1 to 4096 (12 bits).

The 1-MHz signal is also divided by 1000. This provides a 1-kHz signal which is taken to a monostable multivibrator configured to provide a 0.1- μ sec pulse. The 0.1- μ sec, 1-kHz pulse is used to set a D flip-flop. The flip-flop is reset by the three-stage binary divider through a monostable multivibrator configured to provide a 0.1- μ sec pulse. This results in a 1-kHz signal with a pulse width equal to the reciprocal of the divisor of the three-stage binary counter in microseconds. Thus the signal is programmable with a pulse width from 1 μ sec to full on with a repetition rate of 1 kHz.

The digital PWM card provides a resolution of 1 μ sec, which is 10 times better than required. The pulse-width range exceeds the requirements (especially at the low end) by a wide margin. A detailed description of the digital

pulse-width modulation card circuit is included in appendix A and a description of the prerequisite software is included in appendix C.

CO₂ Laser Digital Pulse-Width Modulation Closed-Loop Control System Test Result

Figure 14(a) is a plot of the typical stabilized laser output as a function of time, beginning from startup with digital pulse-width modulation closed-loop control. There is a 28 percent overshoot at startup, and the output is within ± 2 percent of the setpoint after 5 sec. Altering the water flow to simulate Spacelab conditions resulted in the performance characteristics shown in figure 14(b). Thus, the system meets the science requirements.

CO₂ Laser Analog Pulse-Width Modulation (PWM) Closed-Loop Control System

An analog PWM closed-loop control system for the CO₂ laser was configured with the analog controller already described and a linear PWM circuit. A block diagram of the system is shown in figure 15. A block diagram of the linear PWM circuit is shown in figure 16. The ramp generator section produces a symmetrical triangular waveform with a frequency of 1 kHz. This signal is taken to the input of the comparator and compared with the analog controller voltage. The comparator produces a rectangular pulse train. The duty cycle varies from 0 percent (with a control voltage of approximately 6.0 V) to 100 percent (with a control voltage of approximately 2.4 V). This signal is taken to a buffer which is compatible with the PWM input of the 40-MHz laser RF power supply. A detailed description of the linear PWM circuit is included in appendix B.

CO₂ Laser Analog Pulse-Width Modulation Control System Test Results

Figure 17(a) is a typical plot of the stabilized laser output as a function of time, beginning from startup with closed-loop analog pulse-width modulation control. There is a 12 percent overshoot at startup and the output is within ± 2 percent of the setpoint after 10 sec. Altering the water flow to simulate Spacelab conditions resulted in the performance characteristics shown in figure 17(b). Thus, the system meets the science requirements.

CO₂ Laser Variable Beam Intensity Control

The output power of the laser can be controlled by varying the input voltage of the 40-MHz RF power supply. The nominal input voltage is 28 V dc. The output power of the laser is reduced almost linearly with the input voltage down to approximately 18 V dc. The output power of the laser then reduces almost exponentially down to 0 W at approximately 13.5 V. A typical laser output power versus input voltage plot is shown in figure 18. The characteristic also changes with age and laser temperature.

The variable beam intensity control scheme is best suited for control over the upper power regions of the laser because of the nonlinear response at lower power.

Modifying the 40-MHz RF power supply circuit could possibly result in a more linear response. The unmodified circuit undergoes various nonlinearities at the lower input voltages, thus contributing to the overall nonlinearity.

Permitting the input voltage to fall too low causes the laser to shut down and then requires that a threshold voltage level be achieved to restart the laser. This hysteresis effect must be avoided because it causes control problems.

A digital variable beam intensity closed-loop control system for the CO₂ laser was developed. This was implemented by controlling a voltage programmable power supply using the digital controller already described. A block diagram of the system is shown in figure 19. The computer provides the STD bus with the desired power data. These are converted into the appropriate analog signal via the STD bus digital-to-analog converter card. The analog signal is taken to the voltage programmable power supply. The output of the power supply is used to power the 40-MHz laser RF power supply.

CO₂ Laser Digital Variable Beam Intensity Closed-Loop Control System Test Results

A description of the software required to implement the digital variable beam intensity control system is included in appendix C. Figure 20(a) is a plot of the typical stabilized laser output as a function of time, beginning from startup with closed-loop digital variable beam intensity control. There is a 28 percent overshoot at startup and the output is within ± 2 percent of the setpoint after 5 sec. Altering the water flow to simulate Spacelab conditions resulted in the performance characteristics shown in figure 20(b). Thus, the system meets the science requirements.

CO₂ Laser Analog Variable Beam Intensity Closed-Loop Control System

An analog variable beam intensity closed-loop control system for the CO₂ laser was developed. This was implemented by controlling a voltage programmable power supply with the analog controller already described. A block diagram of the system is shown in figure 21. The output of the analog controller is taken to the voltage programmable power supply. The output of the power supply feeds the 40-MHz laser power supply.

CO₂ Laser Analog Variable Beam Intensity Closed-Loop Control System Test Results

Figure 22(a) is a plot of the typical stabilized laser output as a function of time, beginning from startup with closed-loop analog variable beam intensity control. There is a 12 percent overshoot at startup, and the output is within ± 2 percent of the setpoint after 10 sec.

Altering the water flow to simulate Spacelab conditions resulted in the performance characteristics shown in figure 22(b). Thus, the system meets the science requirements.

CONCLUDING REMARKS

The four CO₂ laser control configurations that were evaluated all performed adequately to meet the science requirements. Other considerations accounted for the selection of the analog variable beam intensity closed-loop control system to be selected for the engineering model of the STDCE.

The pulse-width modulation-based control systems were rejected for application in the engineering model to ensure minimization of electromagnetic interference (EMI). The flight model hardware must meet the stringent EMI requirements of MSFC-SPEC-521A. PWM techniques inherently tend to produce high EMI levels because of the voltage and current characteristics associated with the technique.

The digital control systems were rejected for the engineering model because of reliability concerns. The digital control systems considered were based upon the use of the existing STD bus system. A stand-alone analog controller was desired to eliminate the possibility of losing control of the laser as a result of a failure in the STD bus system. A stand-alone digital controller could have been used, but the simplicity, reliability, and availability of the analog controller made it the obvious choice for this application.

The analog variable beam intensity closed-loop control system was the control configuration selected for the engineering model. The test results indicate that the science requirements can be met with this system.

The configuration of the engineering model CO₂ laser control system is shown in the block diagram in figure 23. The setpoint is entered into the analog controller from a digital-to-analog converter in the STD bus. The output of the analog controller drives the trim input of a dc-dc power converter. The output of the dc-dc converter is proportional to the trim voltage regardless of power bus fluctuations. This voltage powers the CO₂ laser RF power supply which regulates the output power of the laser.

The signal from the power meter is used as the process variable input of the analog controller and the laser power monitor. The signal is taken into the STD bus via an analog-to-digital converter.

The zero is adjusted by means of the STD bus. The power meter signal is examined with the CO₂ laser shut down. An offset voltage is then added to the power meter signal with a digital-to-analog converter to compensate for the deviation from zero.

The flight version of the CO₂ laser, including the control system, will be designed, fabricated, tested, and flight qualified by an outside source.

ACKNOWLEDGMENTS

The authors would like to acknowledge and thank the members of the STDCE design team at the NASA Lewis Research Center for their assistance in the design and evaluation of these control systems.

Special recognition is given to A. Rybar of Aerospace Design and Fabrication, Inc., for his development of the software which was essential to this work.

TABLE I. - LASER LEVELS AS FUNCTION OF
BEAM SPLITTER RATIOS

Laser beam component	Beam splitting ratios		
	6/94	15/85	80/20
	Power levels, W		
Laser power to oil	0.20	0.50	3.00
Laser power to power meter	3.13	2.83	.75
Laser power output	3.33	3.33	3.75

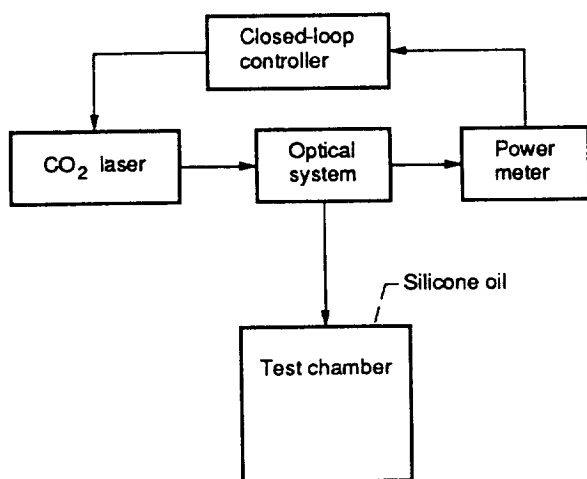


Figure 1.—Block diagram of surface heating system.

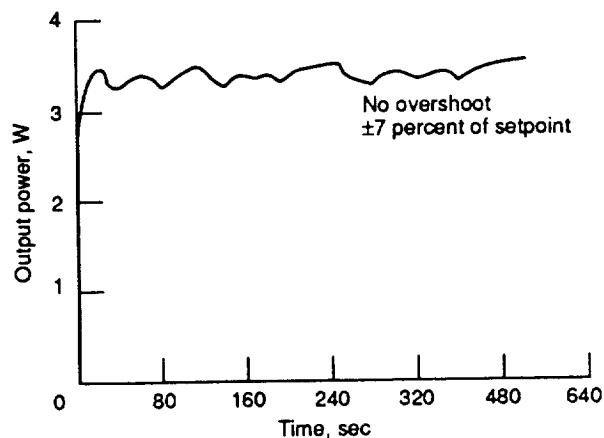


Figure 2.—CO₂ laser output power versus time with open-loop control. Constant base-plate temperature of 75 °F.

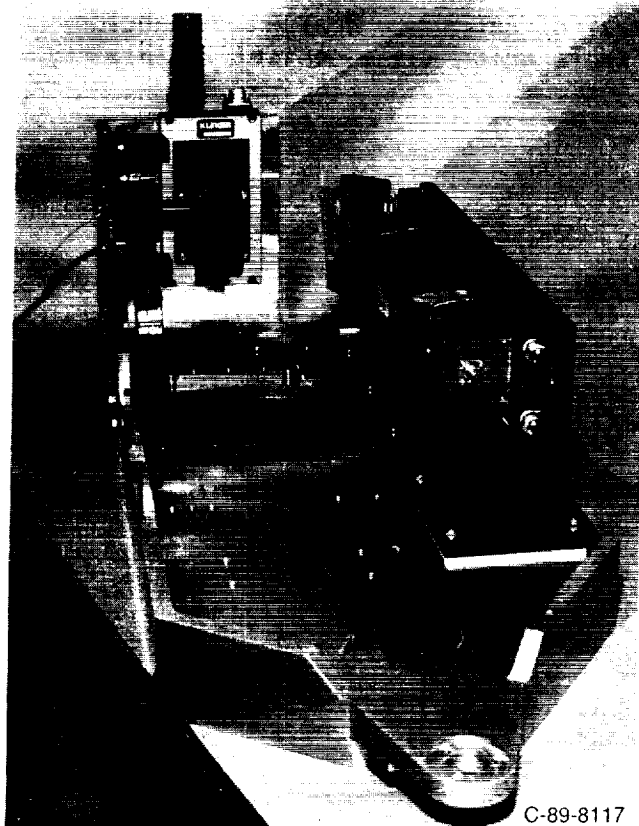


Figure 3.—CO₂ laser.

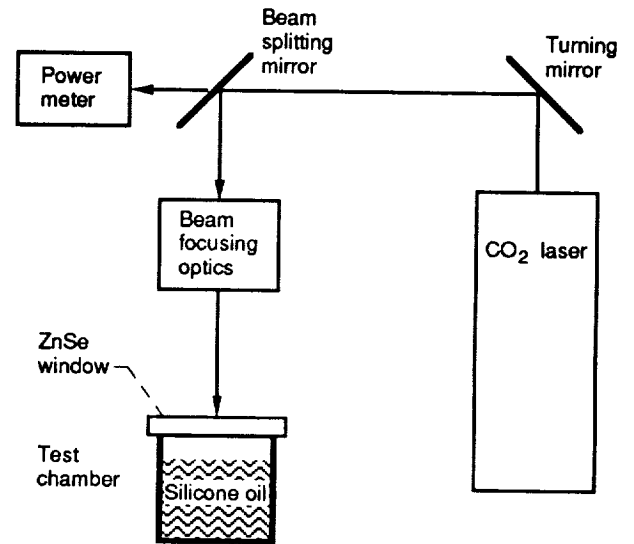


Figure 4.—Block diagram of laser optical system.



Figure 5.—Power meter.



Figure 6.—Copper test chamber.

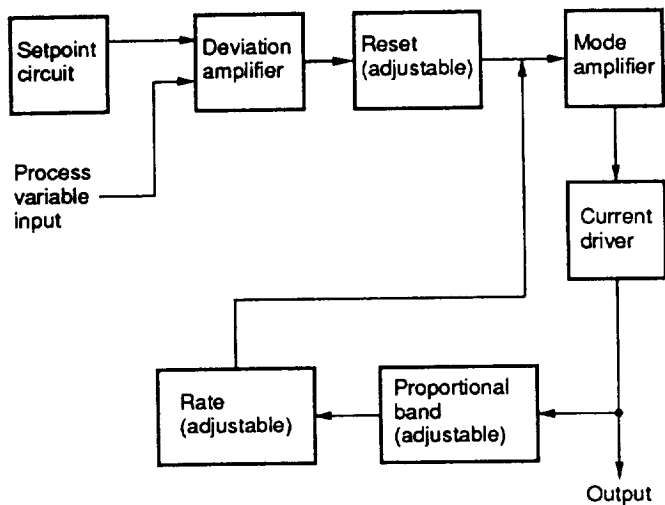


Figure 7.—Block diagram of analog controller.

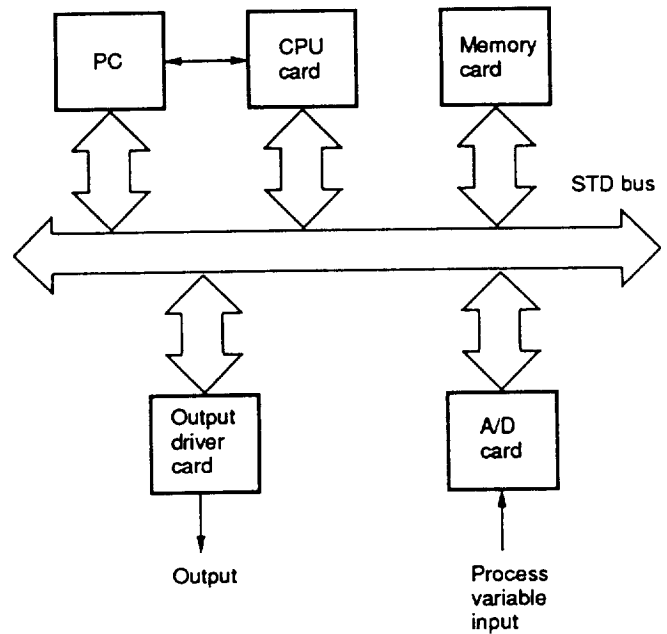


Figure 8.—Block diagram of digital controller.

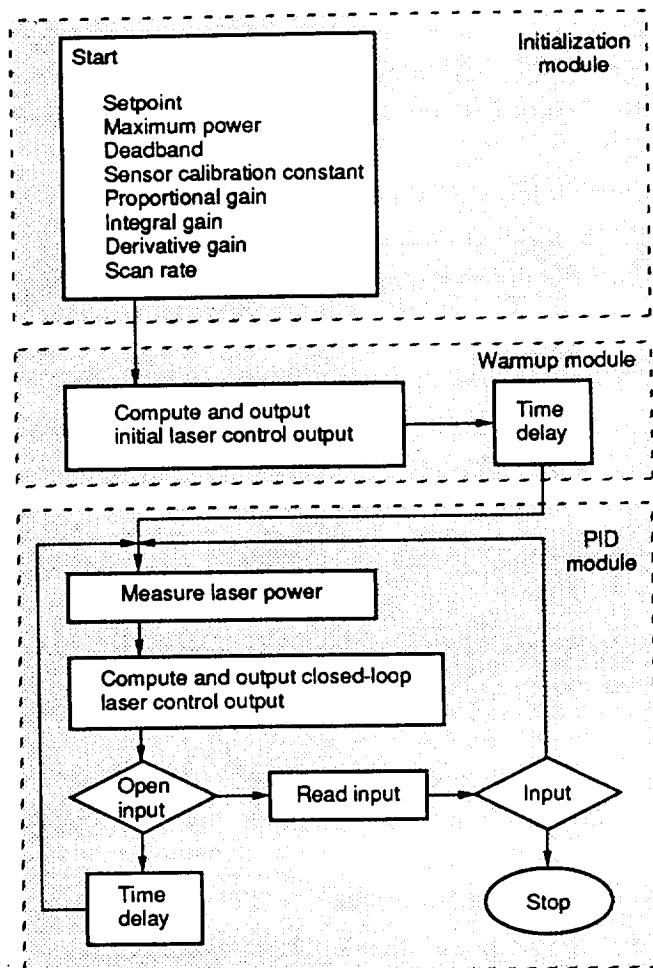


Figure 9.—Flowchart of digital controller software.

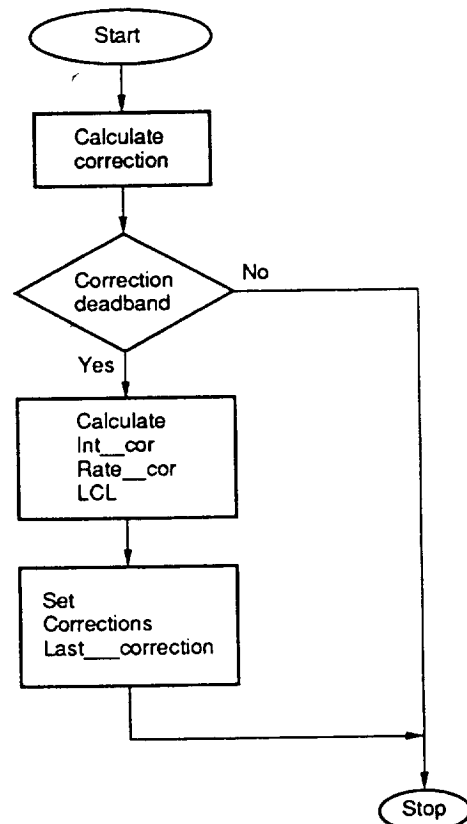


Figure 10.—Digital controller PID algorithm.

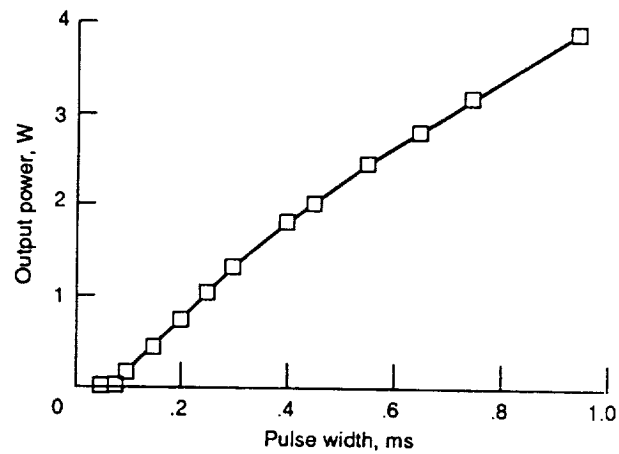


Figure 11.—Open-loop laser output as a function of pulse width. Repetition rate, 1 kHz.

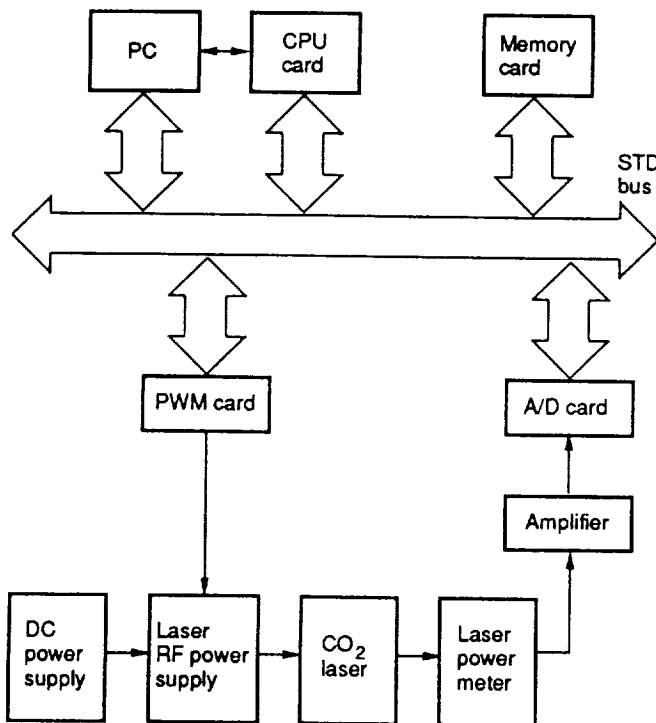


Figure 12.—Digital PWM closed-loop control system for CO₂ laser.

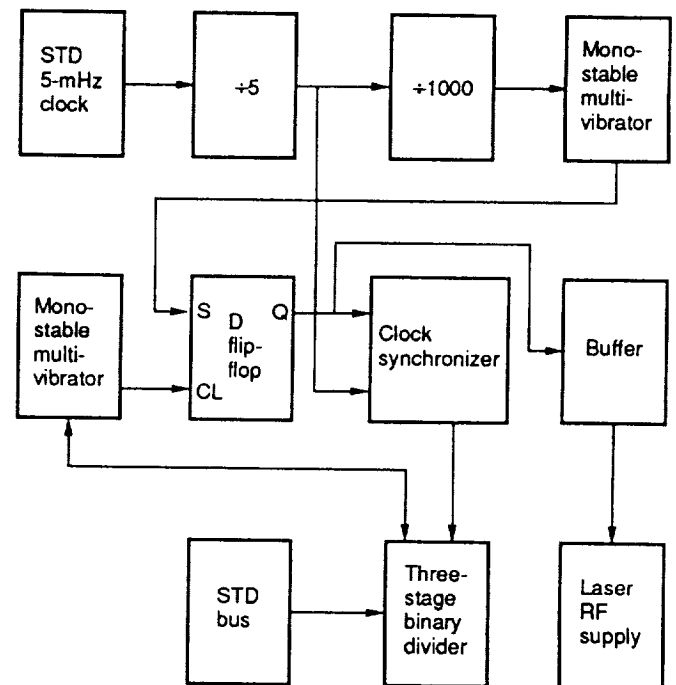


Figure 13.—Block diagram of digital PWM card.

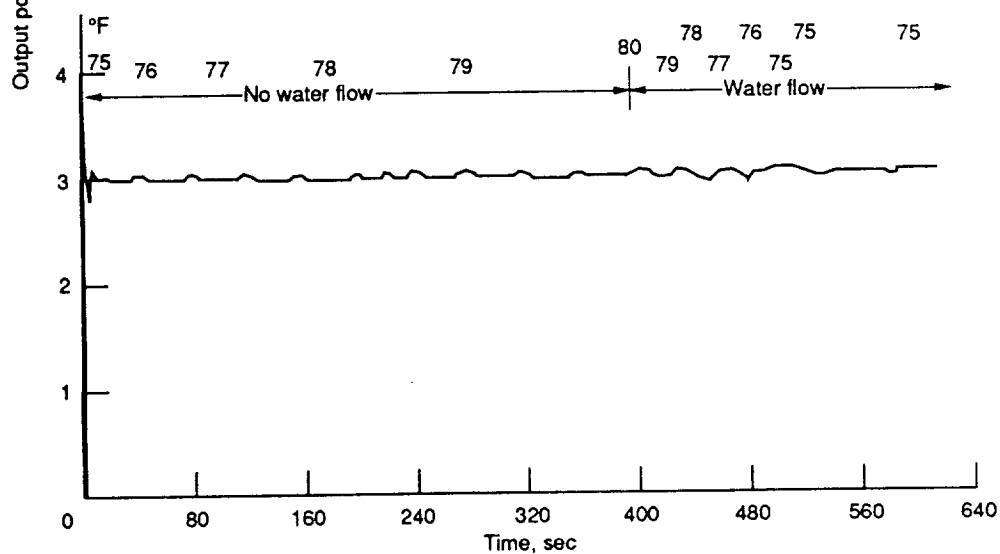
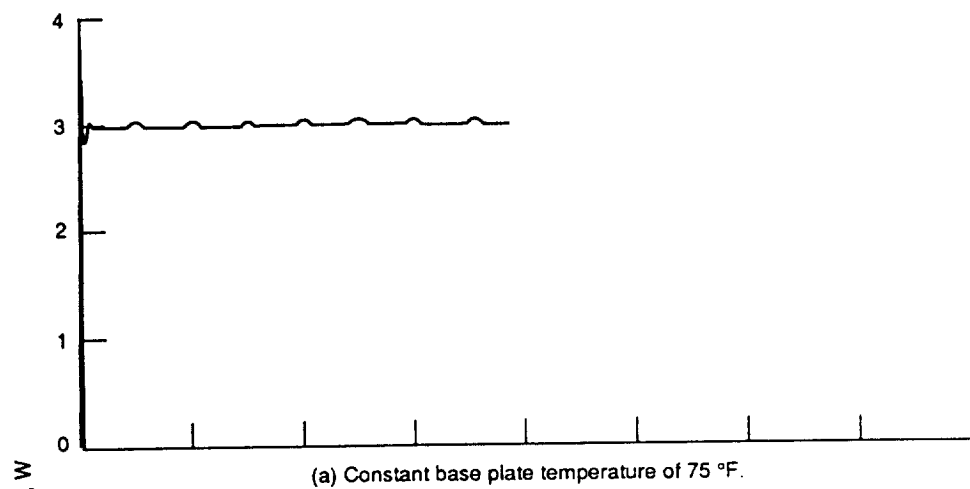


Figure 14.—CO₂ laser output power versus time with digital pulse-width modulation closed-loop control.

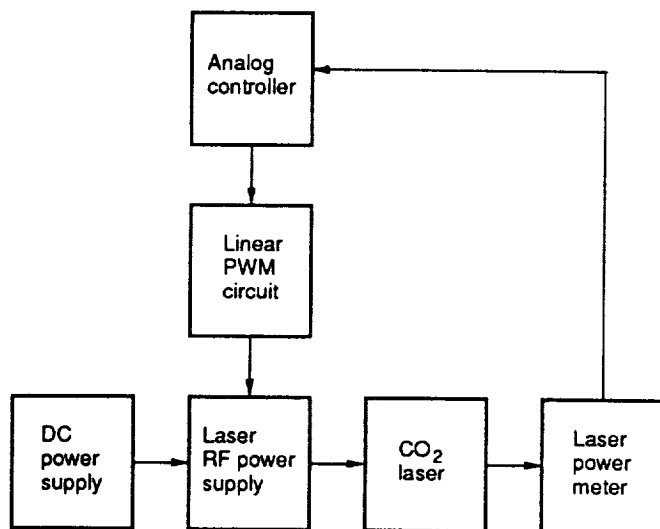


Figure 15.—Block diagram of analog PWM closed-loop control system for CO₂ laser.

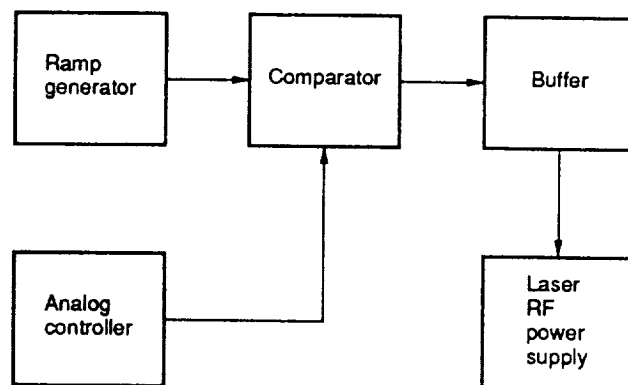


Figure 16.—Block diagram of linear PWM circuit.

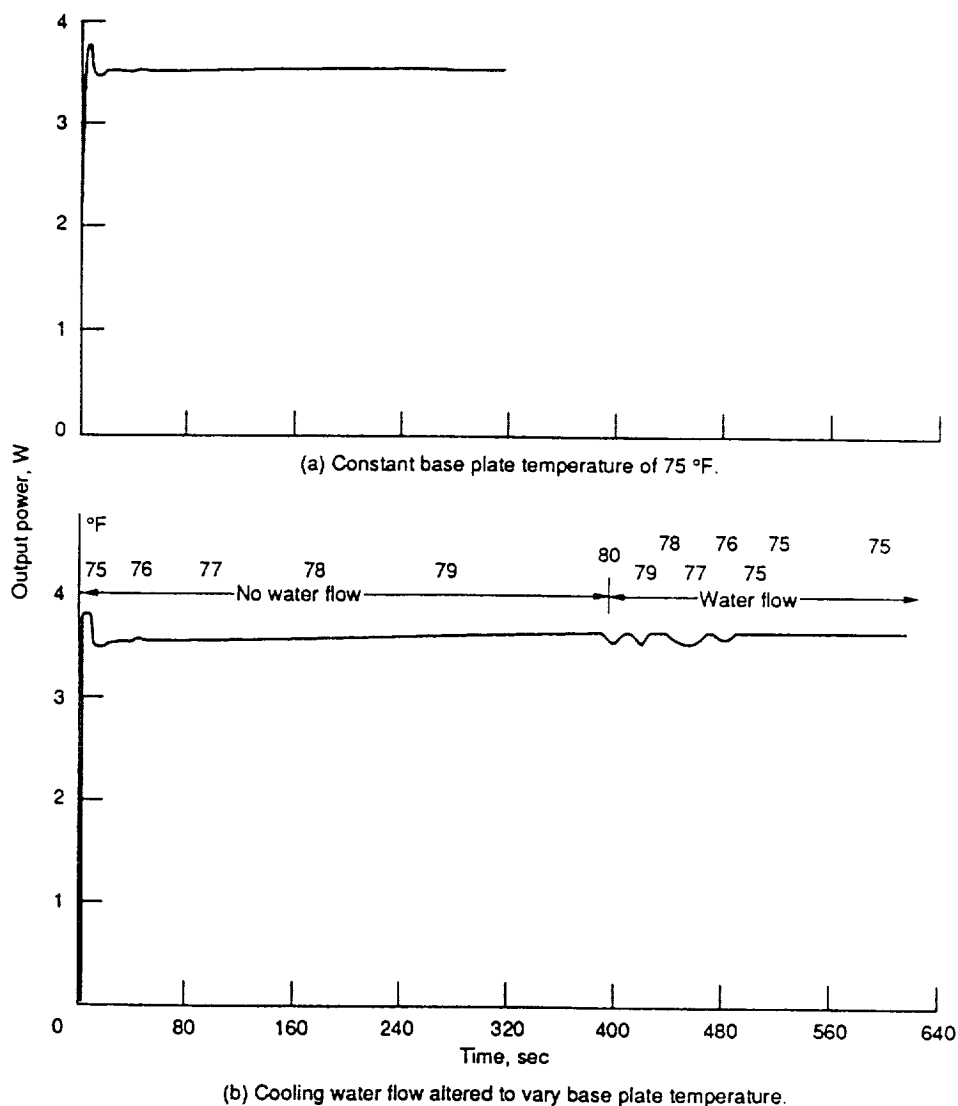


Figure 17.—CO₂ laser output power versus time with closed-loop analog pulse-width modulation control.

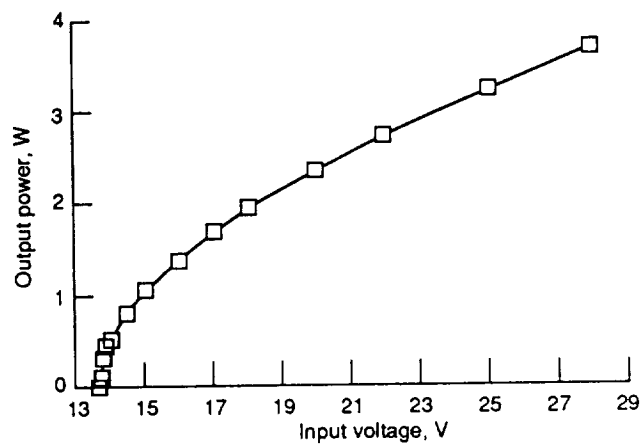


Figure 18.—Open-loop CO₂ laser output as a function of input voltage at constant base plate temperature of 75 °F.

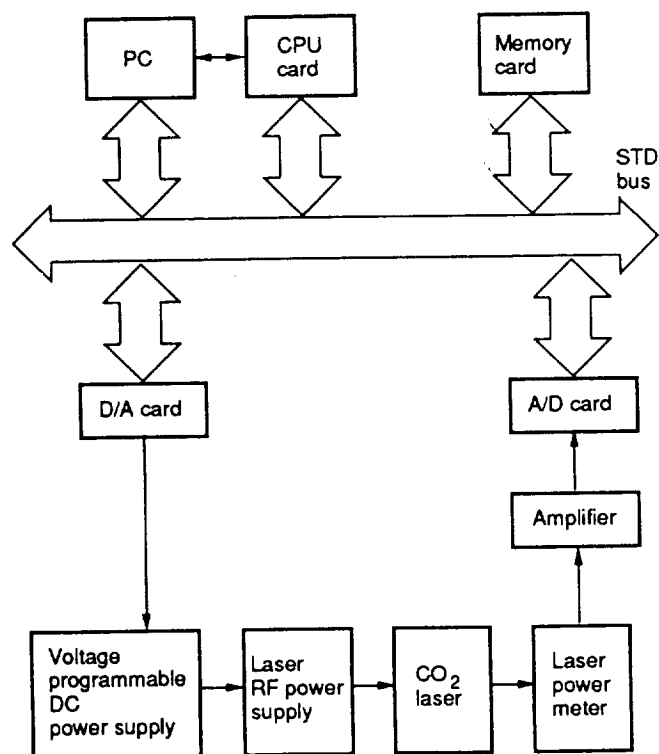


Figure 19.—Block diagram of digital variable beam intensity closed-loop control system for CO₂ laser.

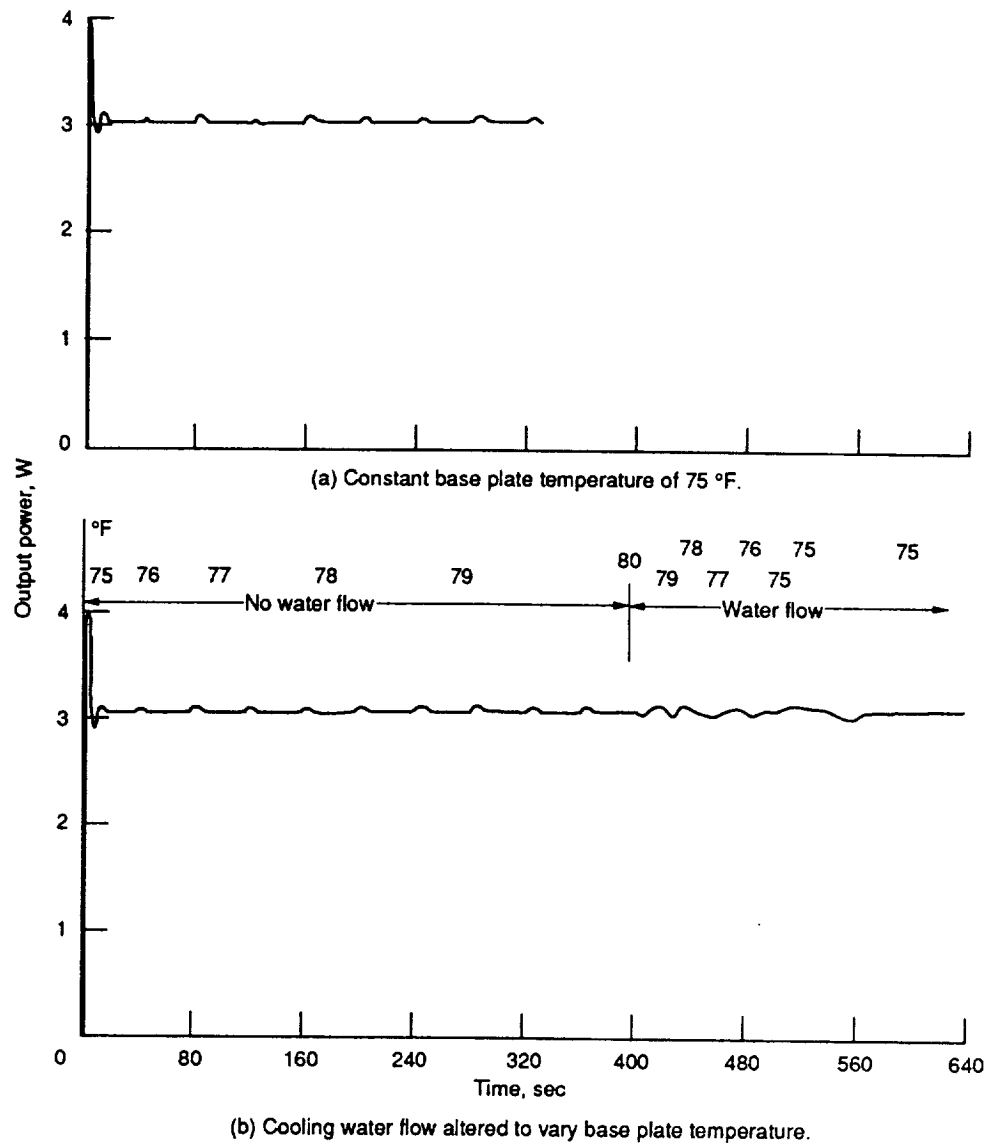


Figure 20.—CO₂ laser output power versus time with digital variable beam intensity closed-loop control.

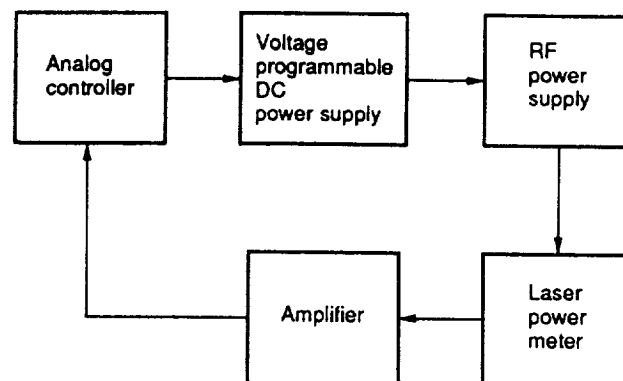


Figure 21.—Block diagram of analog variable beam intensity closed-loop control system for CO₂ laser.

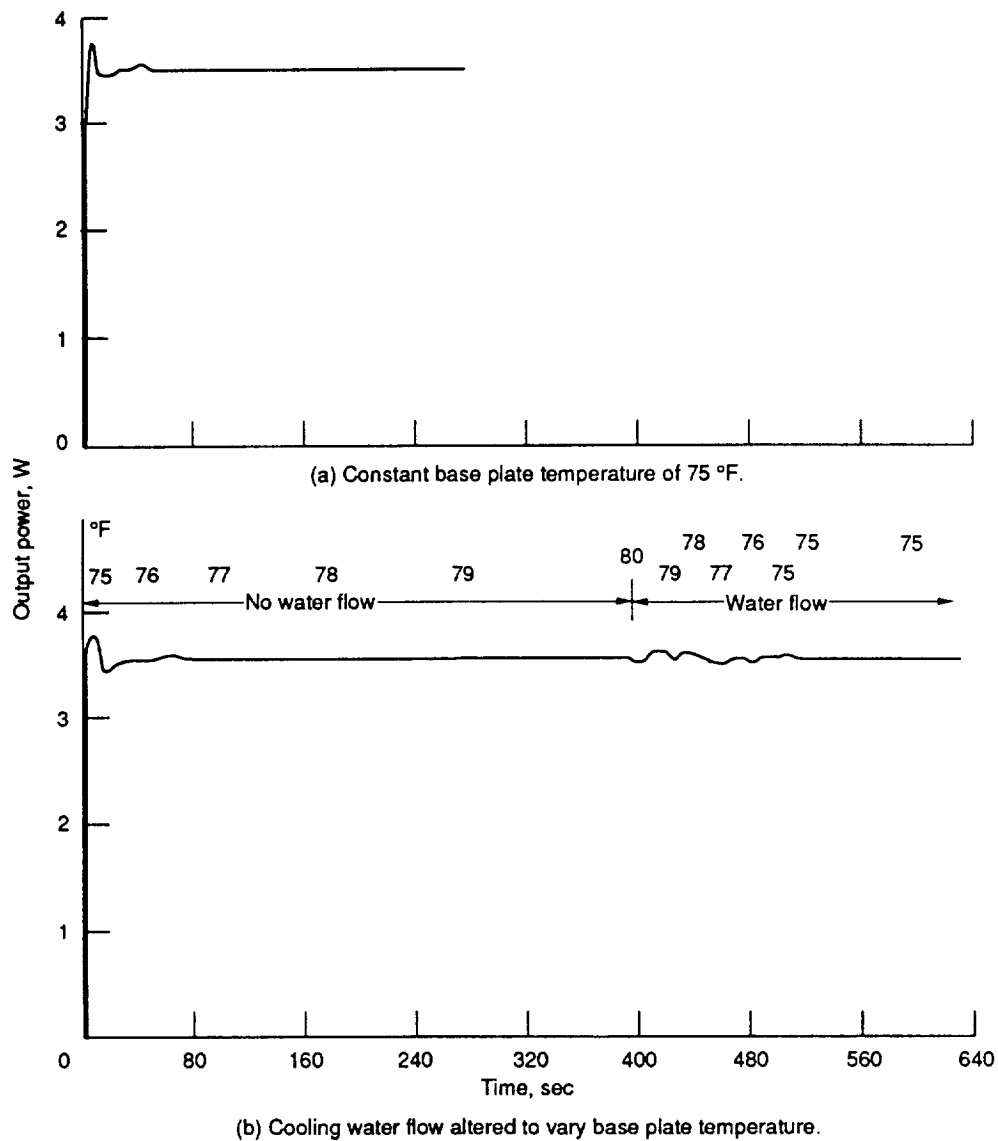


Figure 22.—CO₂ laser output power versus time with analog variable beam intensity closed-loop control.

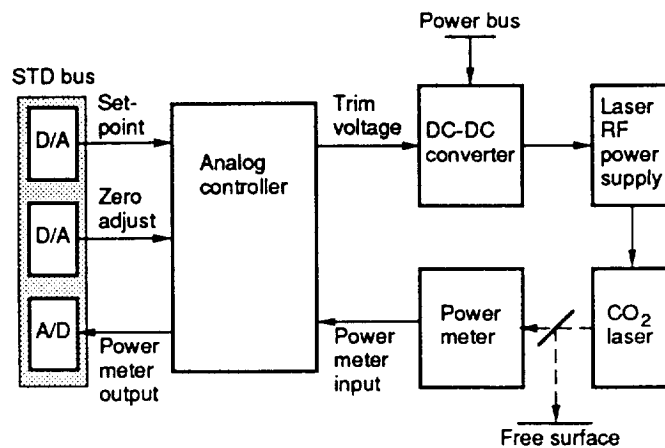


Figure 23.—Block diagram of engineering model CO₂ laser closed-loop control system.

APPENDIX A

DIGITAL PULSE-WIDTH MODULATION (PWM) CARD CIRCUIT

A schematic diagram of the digital PWM card circuit is shown in figure A1. The parts are listed in table A1. The circuit was designed in TTL to be compatible with the Pro-Log 7914 decoded I/O utility STD card used for this application. Low-power Schottky TTL devices have been used in critical high-speed areas. The 7914 is an STD printed circuit card designed for prototyping I/O circuitry. The card provides STD bus buffering and I/O port select decoding. The STD bus provides 8-bit data words and a 5-MHz clock signal.

The 5-MHz clock signal is converted to a 1-MHz signal by a 7490 decade counter configured to divide by 5. The 1-MHz signal is taken to a three-stage binary divider consisting of three cascaded 74LS161 binary dividers via a clock synchronizer. The synchronizer consists of a 74LS74 D flip-flop, a 7404 inverter gate, and a 7402 NOR gate. The dividers are programmed from the STD bus by means of three 7475 quad latches. This permits the frequency division to be programmed from 1 to 4096 (12 bits).

The 1-MHz signal is also divided by 1000 with three cascaded 7490 decade counters each configured to divide by 10. This provides a 1-kHz signal which is taken to a 54121 monostable multivibrator. The 54121 is configured to provide a 0.1- μ sec pulse. The 0.1- μ sec, 1-kHz pulse is used to set a 74LS74 D flip-flop. The flip-flop is reset by the three-stage binary divider with a 54121 monostable multivibrator configured to provide a 0.1- μ sec pulse. This results in a 1-kHz signal with a pulse width equal to the reciprocal of the divisor of the three-stage binary counter in microseconds. Thus, the signal is programmable with a pulse width from 1 μ sec to full on with a repetition rate of 1 kHz. This signal is taken to a 7406 open collector inverter gate via a 7404 inverter gate. The output is capable of handling 30 V. Thus, the output is compatible with the Laakmann model number RF-100-40, 40-MHz power supply.

The general assembly is shown in figure A2. The Pro-Log 7914 decoded I/O utility card has a 3.4- by 3.8-in. area for prototyping with plated-through holes to accommodate 0.042-in. square posts. Wire wrapping is used for this application. The discrete components are soldered onto headers and plugged into wire wrap sockets which must be installed on the card. All signals are provided with the STD bus except for the 28-V power source and the output signal. Separate connectors are provided for the 28-V power source and the output signal connections. The interconnection diagram of the various equipment required for the digital pulse-width modulated laser control system is shown in figure A3. Shielded or coaxial cable is used wherever possible to minimize radiated EMI.

TABLE A1. - PARTS LIST FOR DIGITAL PULSE-WIDTH MODULATED CIRCUIT

Part number	Description	Quantity
IC1 to IC4	Decade counter Texas Instruments no. SN7490AJ NSN 5962-00-430-2600	4
IC5 and IC6	Monostable multivibrator Texas Instruments no. SN54121J NSN 5972-00-369-7706	2
IC7	Dual D edge triggered flip-flop Texas Instruments no. SN74LS74AN	1
IC9 to IC11	Binary counter Texas Instruments no. SN74LS161N	3
IC12 to IC14	Quad latch Texas Instruments no. SN7475N NSN 5962-00-595-8504	3
IC15	Hex inverter Texas Instruments no. SN7404N NSN 5962-00-341-0544	1
R1 and R2	Resistor, fixed, 1/8 W, 5%, 10 k NSN 5905-01-035-5065	2
C3 and C4	Capacitor, fixed, ceramic, 200 V, 10%, 10 pF NSN 5910-00-158-5178	2
101	Socket, integrated circuit, 14 pin dip Augat no. 514-AG10F NSN 5935-00-366-5788	9
102	Socket, integrated circuit, 16 pin dip Augat no. 516-AG10F NSN 5935-00-366-5789	9
103	Socket, integrated circuit, 16 pin dip Augat no. 616-CG1 NSN 5935-00-361-8566	3
104	Decoded I/O utility card, STD BUS Pro-log 7914	1
C1, C2, and C5 to C9	Capacitor, fixed, ceramic, 100 V, 0.010 μ F NSN 5910-00-356-1677	7

TABLE A1. - Continued.

Part number	Description	Quantity
IC8	Quad nor gate Texas Instruments no. SN7402N NSN 5762-01-369-7607	1
IC16	Voltage comparator National Semiconductor no. LM311N NSN 5962-01-069-3883	1
Z1	Zener diode, 5.1 V, 5 W, 5% Motorola no. IN5338B NSN 5961-00-422-3716	1
R3	Resistor, fixed, 1/8 W, 5%, 2.2 k NSN 5905-00-401-7424	1
R4, R5	Resistor, fixed, 1/8 W, 5%, 100 k NSN 5905-00-458-9346	2
R6	Resistor, fixed, 1/8 W, 5%, 47 k NSN 5905-00-617-5093	1
R7	Resistor, fixed, 1/8 W, 5%, 12 k NSN 5905-00-466-1215	1
105	Socket, integrated circuit, 8 pin dip Cambion no. 703-3882-01-03-16 NSN 5935-01-061-1976	1
106	Terminal, wire wrap, 11/16 in. long Vector no. T44 (100 per package) NSN 5940-00-537-4560	1 pkg.
107	Connector adapter, straight BNC jacks/SMA plug Amphenol no. 901-166	1
108, 109	Connector, plug, BNC NSN 5935-01-043-6935	2
110	Connector, receptacle, BNC, bulkhead NSN 5935-00-892-9035	1
111	Connector, receptacle, chassis mount, 4 contacts NSN 5935-00-539-1195	1
112	Connector, plug, 4 contacts NSN 5935-00-846-5340	1

TABLE A1. - Concluded.

Part number	Description	Quantity
113	Bracket, mounting, 3/4 in. W × 1-3/8 in. L × 2 in. H Bud no. AB-549 NSN 5340-00-672-3406	2
114	Cable, 1 pr no. 22 AWG, TW/SHLD NSN 6145-00-866-2302	10 ft
115	Cable, coaxial, RG-59/0 NSN 6145-00-661-0191	10 ft
116	Cable, 1 pr no. 14 AWG, TW/SHLD Belden no. 9314	10 ft

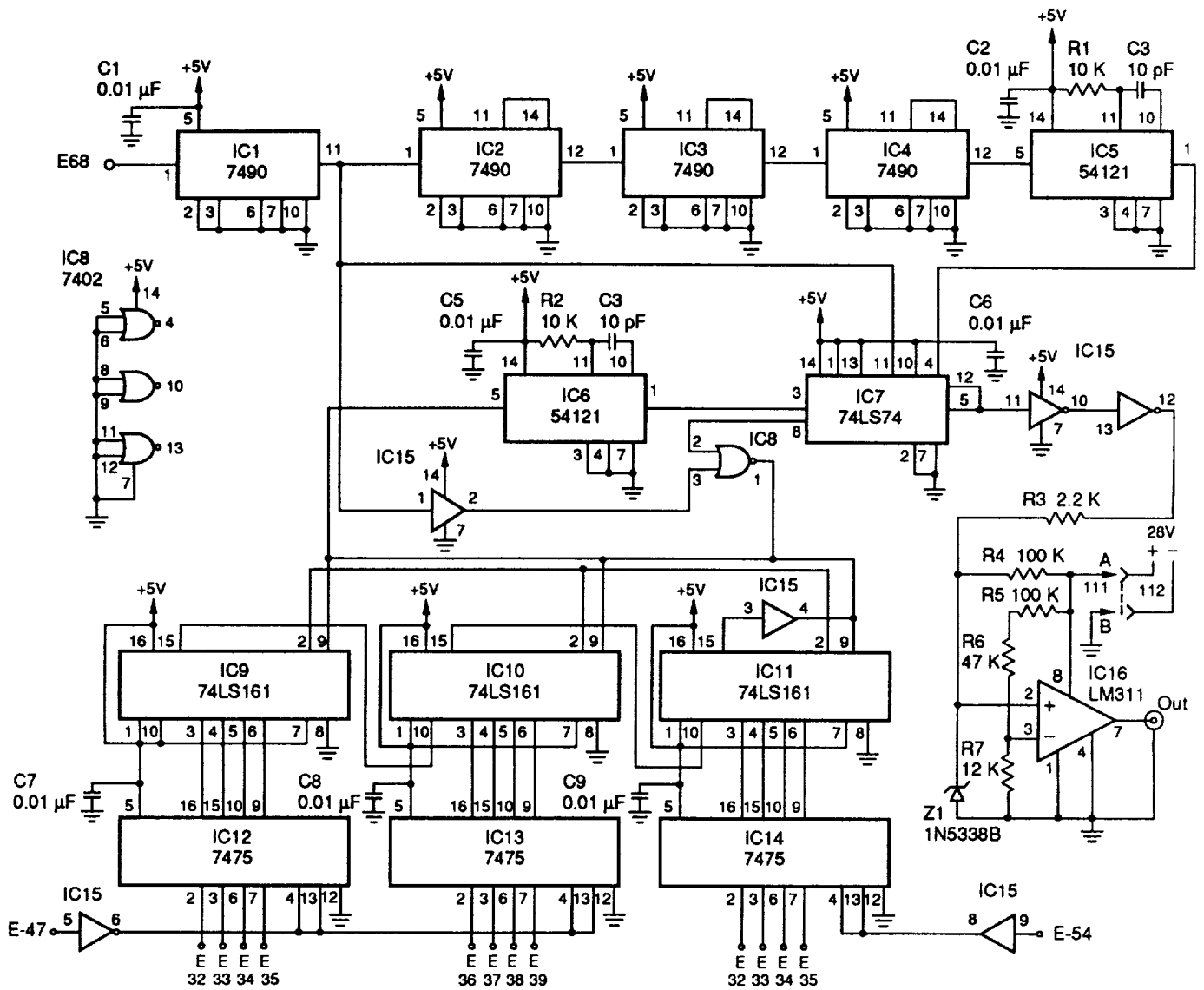


Figure A1.—Schematic diagram of digital pulse-width modulator circuit.

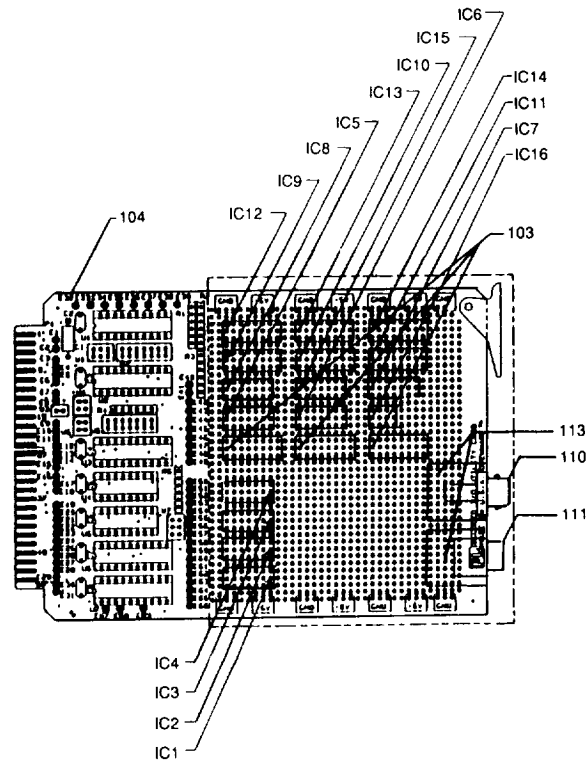


Figure A2.—Assembly diagram of digital pulse-width modulated circuit.

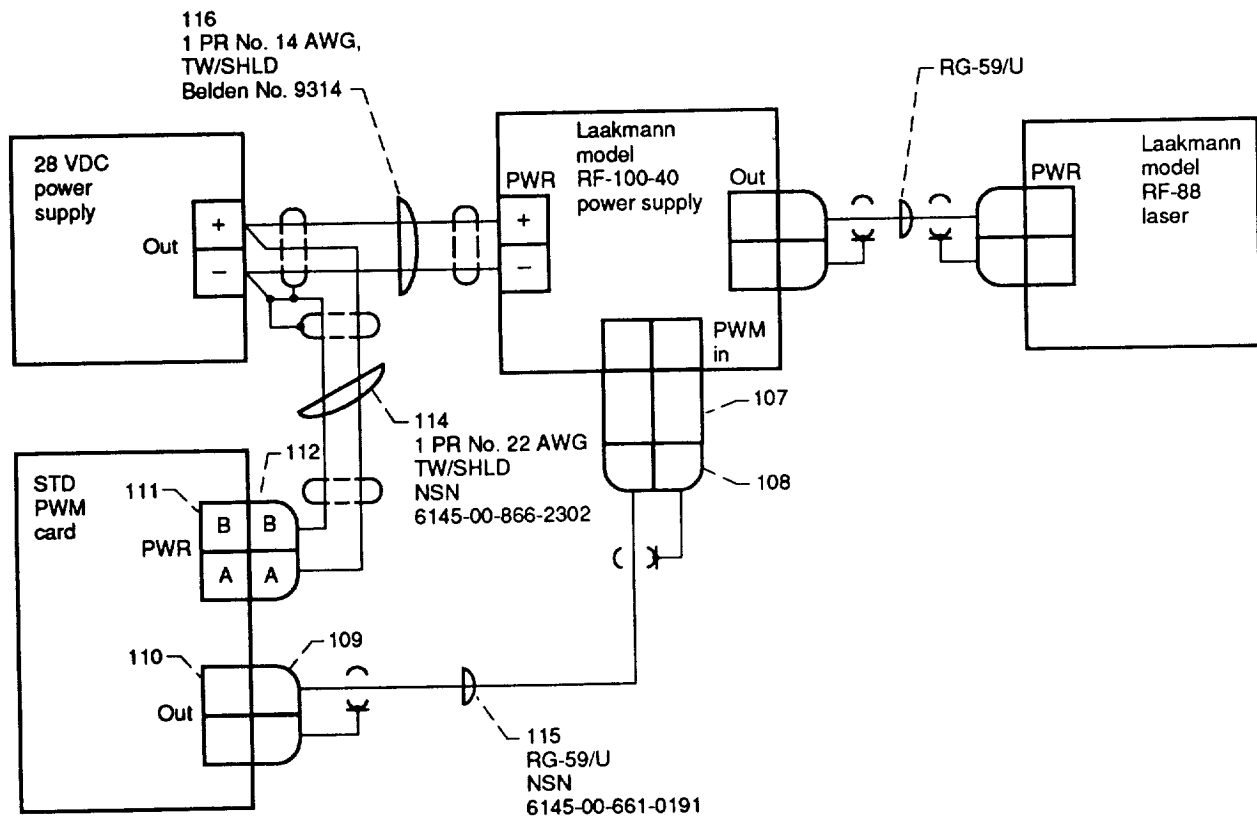


Figure A3.—Interconnection diagram of digital pulse-width modulated circuit.

APPENDIX B

LINEAR PULSE-WIDTH MODULATION (PWM) CIRCUIT

The schematic diagram of the linear PWM circuit is shown in figure B1. The parts are listed in table B1. The circuit is based on an MC3420 switchmode regulator control integrated circuit. The MC3420 contains a ramp generator which produces a symmetrical triangular waveform, and the frequency is determined by an external resistor and capacitor. The output of the ramp generator is taken to the input of a comparator within the MC3420 and then compared with the analog input voltage. The analog input voltage determines the duty cycle of the output. The duty cycle varies from 0 percent (with a control voltage of approximately 6.0 V) to 50 percent (with a control voltage of approximately 2.4 V) for each of the two outputs. A phase splitter is included to obtain two 180° out-of-phase outputs for use in multiple transistor inverter systems. The MC3420 has open collector outputs.

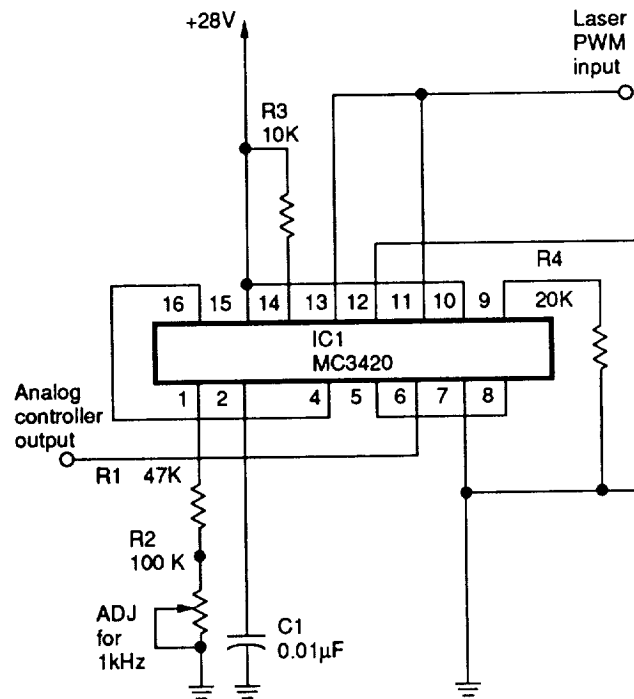
For this application, the two outputs of the MC3420 are tied together so that the output frequency is twice that of each output individually. The output frequency is determined by the expression

$$f_o = \frac{2 \times 0.55}{(R_1 + R_2)C_1}$$

The resistor R2 is adjusted so that the output frequency is 1 kHz. The output transistors of the MC3420 are capable of handling 40 V at 50 mA, which is fully compatible with the PWM input of the 40-MHz laser RF power supply. The interconnection of the various equipment required for the analog pulse-width modulated laser control system is shown in figure B2. Shielded or coaxial cable is used wherever possible to minimize radiated EMI.

TABLE B1. - PARTS LIST FOR LINEAR PULSE-WIDTH MODULATED CIRCUIT

Part number	Description	Quantity
IC1	Switchmode regulator control circuit Motorola no. MC3420	1
R1	Resistor, fixed, 1/4 W, 5%, 47 k NSN 5905-00-141-0717	1
R2	Resistor, adjustable, 1 W, 100 k NSN 5905-01-032-8264	1
R3	Resistor, fixed, 1/2 W, 1%, 10 k NSN 5905-00-038-6136	1
R4	Resistor, fixed, 1/2 W, 1%, 20 k NSN 5905-00-428-1639	1
R5	Capacitor, fixed, ceramic, 100 V, 0.010 μF NSN 5910-00-356-1677	1



Notes:

1. All resistors are 1/4W, 5 percent unless noted otherwise.
2. All capacitors are 50 WVDC, 10 percent ceramic disc unless noted otherwise.

Figure B1.—Schematic diagram of linear pulse-width modulated circuit.

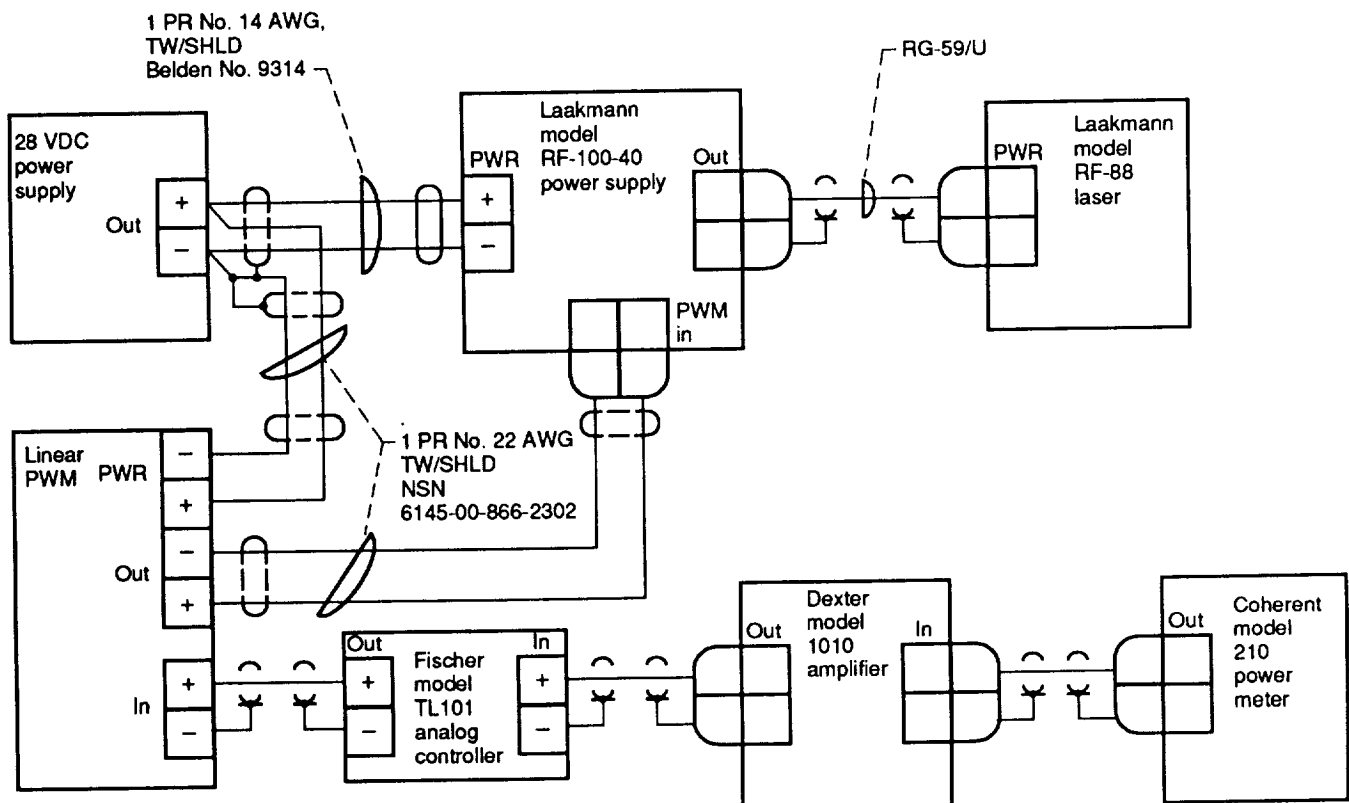


Figure B2.—Interconnection diagram of analog pulse-width modulated laser control system.

APPENDIX C

CO₂ LASER CLOSED-LOOP CONTROL SOFTWARE

Two software routines have been written to allow the use of a Pro-Log ODI STD DOS system to control the output of a CO₂ laser. These two routines are hereby designated as the PWM and voltage control routines. The routines were written and compiled using Turbopascal Version 3.0.

The PWM control routine has been written for the scheme in which the RF power to the CO₂ laser is pulse-width modulated. By pulse-width modulating this RF power, the output power of the CO₂ laser can be controlled. Figure C1 provides an illustration of the hardware configuration utilized for this method.

The voltage control routine has been written for the scheme in which the dc line voltage to the RF supply is controlled. By controlling this voltage, the output power of the CO₂ laser can again be controlled. Figure C2 provides an illustration of the hardware configuration utilized for the method.

DETAILED DESCRIPTION

To simplify the development process, the two software routines have been designed to be essentially identical to each other. The only difference between the two lies within the hardware driver constants. This is because of the difference in the hardware utilized for each control method. The software flowchart for these two routines is illustrated in figure C3. As illustrated in the software flowchart, each routine consists of three major modules. These are the initialization, warmup, and PID modules.

The function of the initialization module is to provide a means to interface with the operator. Here, the operator has the ability to enter the various operational parameters associated with controlling the CO₂ laser. Table C1 illustrates these operational parameters.

The function of the warmup modules is twofold. First, by using the operational parameters, it computes an initial (open-loop) laser control output and outputs it to the appropriate hardware device. Secondly, a 4-sec warmup period is initiated to allow the laser output to stabilize prior to entering into the PID module.

The function of the PID module is threefold. First, by using the operational parameters, it computes the closed-loop laser control output and outputs it to the appropriate hardware device. In computing the laser control output, the PID algorithm defined in appendix A is utilized. Secondly, an opportunity is provided to allow the operator to enter a new setpoint. Finally, a time-delay period is initiated. This time-delay period is programmable, through operator-entered operational parameters, from 0.01 to 2.44 sec. The functions defined for the PID module are continuously repeated until receipt of the stop command from the operator.

{ \$C-, U- }

```
PROGRAM      LASER_POWER_CONTROL;  ( PWM METHOD                                )
                                           ( PROPORTIONAL, INTEGRAL                )
                                           ( AND RATE CONTROL                    )
                                           ( SCAN RATE WITH NO DISPLAY            )
                                           ( INCLUDED                                )
```

```
VAR          SETPOINT:REAL;
              SETP:REAL;
              LASER_OUT_PWR:REAL;
              MAX_PWR:REAL;
              D_BAND:REAL;
              CORRECTION:REAL;
              LAST_CORRECTION:REAL;
              SEN_CALA:REAL;
              LASER_CTRL:INTEGER;
              VOLT_CTRL:INTEGER;
              PROPORTIONAL_GAIN:REAL;
              INTEGRAL_GAIN:REAL;
              RATE:REAL;
              SCAN_RATE:REAL;
              UPDATE_RATE:INTEGER;
              STOP:BOOLEAN;
```

```
PROCEDURE    INPUT_BASE_PARAM(VAR SETPOINT:REAL;
                                VAR D_BAND:REAL;
                                VAR MAX_PWR:REAL;
                                VAR SEN_CALA:REAL;
                                VAR PROPORTIONAL_GAIN:REAL;
                                VAR INTEGRAL_GAIN:REAL;
                                VAR RATE:REAL;
                                VAR UPDATE_RATE:INTEGER;
                                VAR SCAN_RATE:REAL);
```

```
BEGIN        GOTOXY(1,2);              { ENTER PROGRAMMABLE CONSTANTS }
              Writeln('ENTER SETPOINT');
              Readln(SETPOINT);
              Writeln('ENTER DEADBAND');
              Readln(D_BAND);
              Writeln('ENTER MAXIMUM LASER OUTPUT POWER');
              Readln(MAX_PWR);
              Writeln('ENTER SENSOR CALIBRATION CONSTANT A');
              Readln(SEN_CALA);
              Writeln('ENTER PROPORTIONAL GAIN FACTOR');
              Readln(PROPORTIONAL_GAIN);
              Writeln('ENTER INTEGRAL GAIN');
              Readln(INTEGRAL_GAIN);
              Writeln('ENTER RATE');
              Readln(RATE);
              Writeln('ENTER UPDATE RATE: 1 - 50');
              Readln(UPDATE_RATE);
              SCAN_RATE:=0.010+(UPDATE_RATE/50.0)*0.400;

END;
```

```
PROCEDURE    SET_RF_SUP_VOLT(VAR MAX_PWR:REAL;
                              VAR VOLT_CTRL:INTEGER);
```

```

VAR          HL:BOOLEAN;
              LL:BOOLEAN;

BEGIN
              (SET RF SUPPLY OUTPUT VOLTAGE)
              HL:=MAX_PWR<5.0;
              LL:=MAX_PWR>=2.0;
              IF HL AND LL THEN VOLT_CTRL:=1250; {SET RF VOLTAGE = 28VDC}
              HL:=MAX_PWR<2.0;
              LL:=MAX_PWR>=1.0;
              IF HL AND LL THEN VOLT_CTRL:=849;  {SET RF VOLTAGE = 20VDC}
              HL:=MAX_PWR<1.0;
              IF HL THEN VOLT_CTRL:=720;         {SET RF VOLTAGE = 16VDC}

              PORT[$60]:=LO(VOLT_CTRL);          {OUTPUT TO D/A CONVERTER}
              PORT[$61]:=HI(VOLT_CTRL);

END;

PROCEDURE    TIME_DELAY(VAR UPDATE_RATE:INTEGER); {SET UPDATE RATE}

VAR          J:REAL;
              TIME:INTEGER;

BEGIN
              FOR TIME:=1 TO UPDATE_RATE DO
              BEGIN
                  J:=SQRT(TIME);
              END;
END;

PROCEDURE    WARM_UP(VAR SETPOINT:REAL;           {OUTPUT INITIAL POWER }
                     VAR MAX_PWR:REAL;           {SETTING TO LASER }
                     VAR UPDATE_RATE:INTEGER;
                     VAR LASER_CTRL:INTEGER);

VAR          LCC:REAL;
              MSB:BYTE;
              LSB:BYTE;
              X:INTEGER;
              I:INTEGER;

BEGIN
              LCC:=(SETPOINT/MAX_PWR)*750;      {COMPUTE OUTPUT }
              LASER_CTRL:=ROUND(LCC);
              LSB:=(NOT LO(LASER_CTRL));
              MSB:=(NOT HI(LASER_CTRL)) AND $0F;
              PORT[$20]:=LSB;                    {OUTPUT TO PWM }
              PORT[$21]:=MSB;
              I:=ROUND(2.0/((UPDATE_RATE/50.0)*0.400)); {CALCULATE WARM}
                                                         {UP TIME DELAY }
                                                         {USING 2 SECOND}
                                                         {WARM UP TIME }

              FOR X:=1 TO I DO

```

```

        BEGIN
            TIME_DELAY(UPDATE_RATE);
        END;
END;

PROCEDURE    OPERATOR_INPUT(VAR SETPOINT:REAL;      { INPUT NEW SETPOINT }
                        VAR MAX_PWR:REAL;
                        VAR STOP:BOOLEAN);

VAR
    STOP_FLAG:BOOLEAN;

BEGIN
    IF KEYPRESSED THEN                                { CHECK IF KEY HAS }
        BEGIN                                          { BEEN DEPRESSED }
            GOTOXY(1,18);
            WRITELN('ENTER NEW SETPOINT (TYPE 0.0 TO TERMINATE OPERATION)');
            READLN(SETPOINT);
            STOP_FLAG:=SETPOINT=0.0;                  { CHECK IF RUN IS TO }
            IF STOP_FLAG THEN STOP:=TRUE;              { TERMINATED }
        END;
END;

PROCEDURE    INPUT_LASER_POWER(VAR LASER_OUT_PWR:REAL; { MEASURE LASER }
                        VAR SEN_CALA:REAL);              { OUTPUT POWER }

VAR
    STATUS:BYTE;
    RESULT:BYTE;
    OK:BOOLEAN;
    LSB:BYTE;
    MSB:BYTE;
    A_D_CONV:INTEGER;

BEGIN
    PORT[$5B]:=$00;                                { OUTPUT A/D CHANNEL NUMBER }
    REPEAT
        STATUS:=PORT[$5D];                          { CHECK FOR EOC FLAG }
        RESULT:=STATUS AND $80;
        OK:=RESULT=$00;
    UNTIL OK;
    LSB:=PORT[$5C];                                { INPUT LASER OUTPUT POWER }
    MSB:=PORT[$5D];
    MSB:=MSB AND $0F;
    A_D_CONV:=(256*MSB)+LSB;                        { CONVERT TO REAL }
    LASER_OUT_PWR:=((A_D_CONV/4095)*10.0)*SEN_CALA;  { NUMBER }
END;

PROCEDURE    COMPUTE(VAR SETPOINT:REAL;      { CLOSED LOOP CONTROL ROUTINE }
                    VAR SETP:REAL;
                    VAR LASER_OUT_PWR:REAL;
                    VAR MAX_PWR:REAL;
                    VAR CORRECTION:REAL;
                    VAR LAST_CORRECTION:REAL;
                    VAR D_BAND:REAL;
                    VAR LASER_CTRL:INTEGER;
                    VAR PROPORTIONAL_GAIN:REAL;

```

```

        VAR INTEGRAL_GAIN:REAL;
        VAR RATE:REAL;
        VAR SCAN_RATE:REAL);

VAR
    TEST:REAL;
    LCC:REAL;
    INT_COR:REAL;
    RATE_COR:REAL;
    OUT_OF_LIMITS:BOOLEAN;
    UP_OUT_LIM:BOOLEAN;
    LO_OUT_LIM:BOOLEAN;
    MSB:BYTE;
    LSB:BYTE;

BEGIN
    CORRECTION:=SETPOINT-LASER_OUT_PWR; { COMPUTE ERROR }
    TEST:=ABS(CORRECTION); { TEST IF OUT OF LIMITS }
    OUT_OF_LIMITS:=TEST > D_BAND;
    IF OUT_OF_LIMITS THEN
        BEGIN
            { COMPUTE OUTPUT CORRECTION }
            INT_COR:=((CORRECTION+LAST_CORRECTION)/2)*SCAN_RATE
            RATE_COR:=(CORRECTION-LAST_CORRECTION)/SCAN_RATE;
            SETP:=(SETP+(CORRECTION*PROPORTIONAL_GAIN)+
                (INT_COR*INTEGRAL_GAIN)+
                (RATE_COR*RATE));
            LCC:=(SETP/MAX_PWR)*999;

            LO_OUT_LIM:=LCC<1;
            IF LO_OUT_LIM THEN LCC:=1;

            UP_OUT_LIM:=LCC>999;
            IF UP_OUT_LIM THEN LCC:=999;

            LAST_CORRECTION:=CORRECTION;
            LASER_CTRL:=ROUND(LCC); { CONVERT TO INTEGER }
            { BETWEEN 0 AND 999 }
            LSB:=(NOT LO(LASER_CTRL));
            MSB:=(NOT HI(LASER_CTRL)) AND $0F;
            { OUTPUT TO PWM BOARD }
            PORT[$20]:=LSB;
            PORT[$21]:=MSB;
        END;
    END;
END;

BEGIN
    { MAIN PROGRAM }
    CLRSCR;
    PORT[$20]:=$FE;
    PORT[$21]:=$0F;
    STOP:=FALSE;
    WRITELN('LASER OUTPUT POWER CONTROL');
    INPUT_BASE_PARAM(SETPOINT,D_BAND,MAX_PWR,SEN_CALA,
        PROPORTIONAL_GAIN,INTEGRAL_GAIN,RATE,
        UPDATE_RATE,SCAN_RATE);
    SET_RF_SUP_VOLT(MAX_PWR,VOLT_CTRL);

```

```
WARM_UP (SETPOINT, MAX_PWR, UPDATE_RATE, LASER_CTRL) ;
SETP:=SETPOINT;
LAST_CORRECTION:=0.0;
REPEAT
    INPUT_LASER_POWER (LASER_OUT_PWR, SEN_CALA) ;
    COMPUTE (SETPOINT, SETP, LASER_OUT_PWR, MAX_PWR, CORRECTION,
             LAST_CORRECTION, D_BAND, LASER_CTRL,
             PROPORTIONAL_GAIN, INTEGRAL_GAIN,
             RATE, SCAN_RATE) ;
    OPERATOR_INPUT (SETPOINT, MAX_PWR, STOP) ;
    TIME_DELAY (UPDATE_RATE) ;
UNTIL STOP;
PORT[$20]:=$FE;
PORT[$21]:=$0F;
```

END.

{SC-,U-}

```
PROGRAM      LASER_POWER_CONTROL;  {VOLTAGE METHOD
                                     {PROPORTIONAL, INTEGRAL
                                     {AND RATE CONTROL
                                     {SCAN RATE WITH NO DISPLAY
                                     {INCLUDED
                                     }
                                     }
                                     }
                                     }

VAR          SETPOINT:REAL;
             SETP:REAL;
             LASER_OUT_PWR:REAL;
             MAX_PWR:REAL;
             D_BAND:REAL;
             CORRECTION:REAL;
             LAST_CORRECTION:REAL;
             SEN_CAL:REAL;
             LASER_CTRL:INTEGER;
             VOLT_CTRL:INTEGER;
             PROPORTIONAL_GAIN:REAL;
             INTEGRAL_GAIN:REAL;
             RATE:REAL;
             SCAN_RATE:REAL;
             UPDATE_RATE:INTEGER;
             STOP:BOOLEAN;

PROCEDURE    INPUT_BASE_PARAM(VAR SETPOINT:REAL;
                               VAR D_BAND:REAL;
                               VAR MAX_PWR:REAL;
                               VAR SEN_CAL:REAL;
                               VAR PROPORTIONAL_GAIN:REAL;
                               VAR INTEGRAL_GAIN:REAL;
                               VAR RATE:REAL;
                               VAR UPDATE_RATE:INTEGER;
                               VAR SCAN_RATE:REAL);

BEGIN
    GOTOXY(1,2);                      {ENTER PROGRAMMABLE CONSTANTS}
    WRITELN('ENTER SETPOINT');
    READLN(SETPOINT);
    WRITELN('ENTER DEADBAND');
    READLN(D_BAND);
    WRITELN('ENTER MAXIMUM LASER OUTPUT POWER');
    READLN(MAX_PWR);
    WRITELN('ENTER SENSOR CALIBRATION CONSTANT');
    READLN(SEN_CAL);
    WRITELN('ENTER PROPORTIONAL GAIN FACTOR');
    READLN(PROPORTIONAL_GAIN);
    WRITELN('ENTER INTEGRAL GAIN');
    READLN(INTEGRAL_GAIN);
    WRITELN('ENTER RATE');
    READLN(RATE);
    WRITELN('ENTER UPDATE RATE: 1 - 50');
    READLN(UPDATE_RATE);
    SCAN_RATE:=0.010+(UPDATE_RATE/50)*0.400;

END;

PROCEDURE    TIME_DELAY(VAR UPDATE_RATE:INTEGER);  {SET UPDATE RATE}
```

```

VAR          J:REAL;
            TIME:INTEGER;

BEGIN
    FOR TIME:=1 TO UPDATE_RATE DO
    BEGIN
        J:=SQRT(TIME);
    END;
END;

PROCEDURE    WARM_UP(VAR SETPOINT:REAL;          {OUTPUT INITIAL POWER   }
                   VAR MAX_PWR:REAL;             {SETTING TO LASER       }
                   VAR UPDATE_RATE:INTEGER;
                   VAR LASER_CTRL:INTEGER);

VAR          LCC:REAL;
            MSB:BYTE;
            LSB:BYTE;
            I:INTEGER;
            X:INTEGER;

BEGIN
    LCC:=(SETPOINT/MAX_PWR)*1200;                {COMPUTE OUTPUT          }
    LASER_CTRL:=ROUND(LCC);
    LSB:=LO(LASER_CTRL);
    MSB:=HI(LASER_CTRL) AND $0F;
    PORT[$20]:=LSB;                             {OUTPUT TO D/A          }
    PORT[$21]:=MSB;                             {BOARD                  }

                                           {CALCULATE WARM UP}
                                           {UP TIME DELAY      }
                                           {USING 4 SECOND     }
                                           {WARM UP TIME       }

    I:=ROUND(4.0/((UPDATE_RATE/50.0)*0.400));
    FOR X:=1 TO I DO
    BEGIN
        TIME_DELAY(UPDATE_RATE);
    END;
END;

PROCEDURE    OPERATOR_INPUT(VAR SETPOINT:REAL;   {INPUT NEW SETPOINT   }
                           VAR MAX_PWR:REAL;
                           VAR STOP:BOOLEAN);

VAR          STOP_FLAG:BOOLEAN;

BEGIN
    IF KEYPRESSED THEN                          {CHECK IF KEY HAS      }
    BEGIN                                        {BEEN DEPRESSED       }
        GOTOXY(1,18);
        WRITELN('ENTER NEW SETPOINT (TYPE 0.0 TO TERMINATE OPERATION)');
        READLN(SETPOINT);
        STOP_FLAG:=SETPOINT=0.0;                {CHECK IF RUN IS TO   }
    END;
END;

```

```

        IF STOP_FLAG THEN STOP:=TRUE;      {TERMINATED }
END;

PROCEDURE INPUT_LASER_POWER(VAR LASER_OUT_PWR:REAL; {MEASURE LASER }
                           VAR SEN_CAL:REAL);      {OUTPUT POWER }

VAR
    STATUS:BYTE;
    RESULT:BYTE;
    OK:BOOLEAN;
    LSB:BYTE;
    MSB:BYTE;
    A_D_CONV:INTEGER;

BEGIN
    PORT[$5B]:=$00;                          {OUTPUT A/D CHANNEL NUMBER }
    REPEAT
        STATUS:=PORT[$5D];                    {CHECK FOR EOC FLAG }
        RESULT:=STATUS AND $80;
        OK:=RESULT=$00;
    UNTIL OK;
    LSB:=PORT[$5C];                          {INPUT LASER OUTPUT POWER }
    MSB:=PORT[$5D];
    MSB:=MSB AND $0F;
    A_D_CONV:=(256*MSB)+LSB;
    LASER_OUT_PWR:=((A_D_CONV/4095)*10.0)*SEN_CAL; {CONVERT TO REAL}
END;                                         {NUMBER }

PROCEDURE COMPUTE(VAR SETPOINT:REAL; {CLOSED LOOP CONTROL ROUTINE}
                  VAR SETP:REAL;
                  VAR LASER_OUT_PWR:REAL;
                  VAR MAX_PWR:REAL;
                  VAR CORRECTION:REAL;
                  VAR LAST_CORRECTION:REAL;
                  VAR D_BAND:REAL;
                  VAR LASER_CTRL:INTEGER;
                  VAR PROPORTIONAL_GAIN:REAL;
                  VAR INTEGRAL_GAIN:REAL;
                  VAR RATE:REAL;
                  VAR SCAN_RATE:REAL);

VAR
    TEST:REAL;
    LCC:REAL;
    INT_COR:REAL;
    RATE_COR:REAL;
    OUT_OF_LIMITS:BOOLEAN;
    UP_OUT_LIM:BOOLEAN;
    LO_OUT_LIM:BOOLEAN;
    MSB:BYTE;
    LSB:BYTE;

BEGIN
    CORRECTION:=SETPOINT-LASER_OUT_PWR; {COMPUTE ERROR }
    TEST:=ABS(CORRECTION);               {TEST IF OUT OF LIMITS}
    OUT_OF_LIMITS:=TEST > D_BAND;

```

```
IF OUT_OF_LIMITS THEN
  BEGIN
```

```
      { COMPUTE OUTPUT CORRECTION }
      INT_COR:=( (CORRECTION+LAST_CORRECTION)/2)*SCAN_RATE;
      RATE_COR:=(CORRECTION-LAST_CORRECTION)/SCAN_RATE;
      SETP:=(SETP+(CORRECTION*PROPORTIONAL_GAIN)+
              (INT_COR*INTEGRAL_GAIN)+
              (RATE_COR*RATE));
      LCC:=(SETP/MAX_PWR)*1200;

      LO_OUT_LIM:=LCC<600;
      IF LO_OUT_LIM THEN LCC:=600;

      UP_OUT_LIM:=LCC>1200;
      IF UP_OUT_LIM THEN LCC:=1200;

      LAST_CORRECTION:=CORRECTION;
      LASER_CTRL:=ROUND(LCC);      { CONVERT TO INTEGER      }
                                   { BETWEEN 0 AND 4095      }

      LSB:=LO(LASER_CTRL);
      MSB:=HI(LASER_CTRL) AND $0F;
                                   { OUTPUT TO D/A BOARD      }

      PORT[$20]:=LSB;
      PORT[$21]:=MSB;
```

```
  END;
```

```
END;
```

```
BEGIN
```

```
  {MAIN PROGRAM}
  CLRSCR;
  PORT[$20]:=$00;
  PORT[$21]:=$00;
  STOP:=FALSE;
  WRITELN('LASER OUTPUT POWER CONTROL');
  INPUT_BASE_PARAM(SETPPOINT,D_BAND,MAX_PWR,SEN_CAL,
                   PROPORTIONAL_GAIN,INTEGRAL_GAIN,
                   RATE,UPDATE_RATE,SCAN_RATE);
  WARM_UP(SETPPOINT,MAX_PWR,UPDATE_RATE,LASER_CTRL);
  SETP:=SETPPOINT;
  LAST_CORRECTION:=0.0;
  REPEAT
    INPUT_LASER_POWER(LASER_OUT_PWR,SEN_CAL);
    COMPUTE(SETPPOINT,SETP,LASER_OUT_PWR,MAX_PWR,CORRECTION,
            LAST_CORRECTION,D_BAND,LASER_CTRL,
            PROPORTIONAL_GAIN,INTEGRAL_GAIN,
            RATE,SCAN_RATE);
    OPERATOR_INPUT(SETPPOINT,MAX_PWR,STOP);
    TIME_DELAY(UPDATE_RATE);
  UNTIL STOP;
  PORT[$20]:=$00;
  PORT[$21]:=$00;
```

```
END.
```

TABLE C1. - SOFTWARE INITIALIZATION PARAMETERS

Parameter	Range
Setpoint, W	0.0 to 5.0
Deadband, W	0.001 to 1.0
Maximum laser output power, W	0.0 to 10.0
Sensor calibration constant, ^a W/V	0.0 to 1000.0
Proportional gain	0.0 to 1000.0
Integral gain	0.0 to 1000.0
Rate	0.0 to 1000.0
Update rate ^b	1 to 50

^aOutput power = (Sensor calibration constant) × (Sensor output voltage).

^bUpdate/Second + 0.010 sec + (Update rate/50) × 0.4 sec.

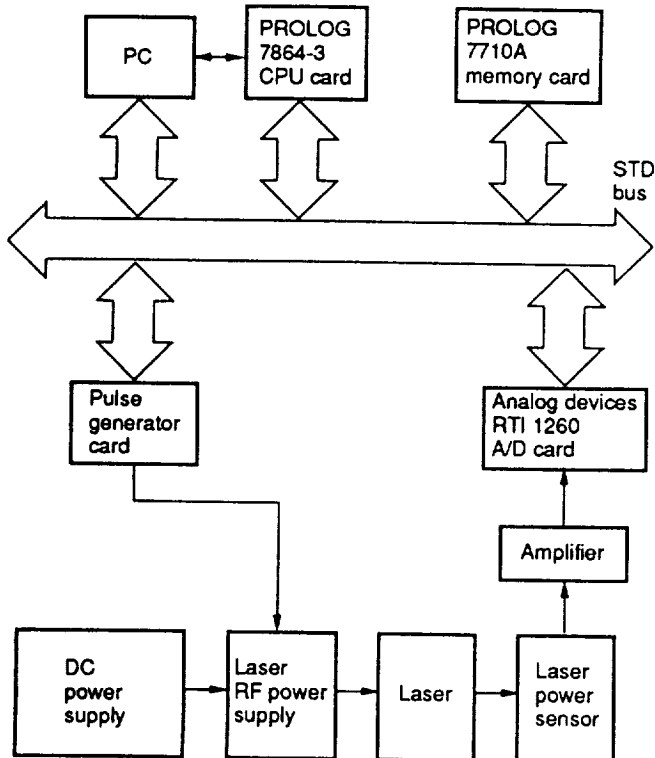


Figure C1.—Pulse-width modulator control scheme.

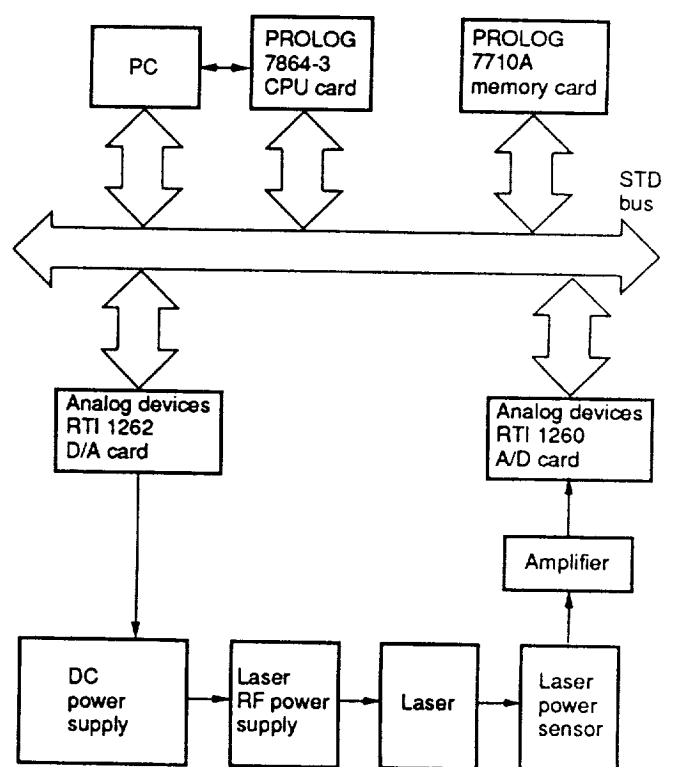
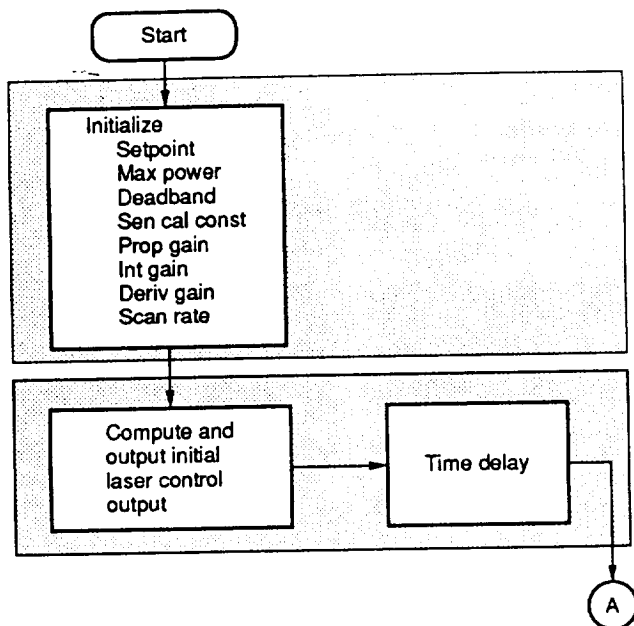
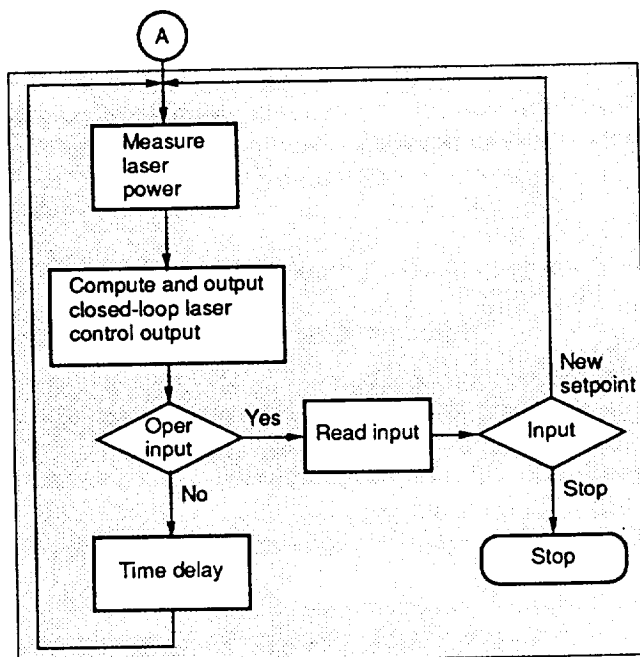


Figure C2.—Voltage control scheme.



(a) Initialization and warmup modules.



(b) PID module.

Figure C3.—Software flowchart.

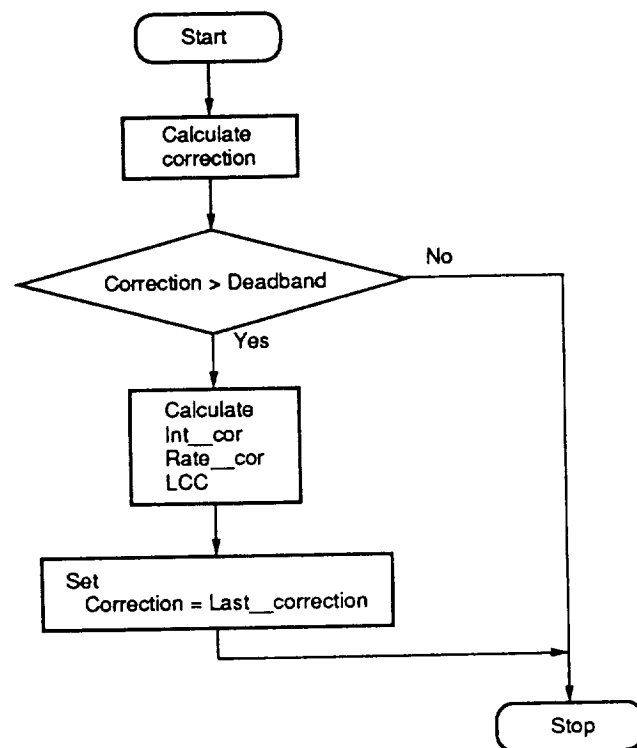


Figure C4.—PID algorithm.

PID ALGORITHM

The classical PID algorithm is defined by equation (1).

$$1. \quad C = +K_p E + K_i E t + K_d \frac{de}{dt}$$

where

C control output
 E error (setpoint-feedback)
 Kp proportional gain
 Ki integral gain
 Kd derivative gain or rate
 t time

Since this equation is only really valid for continuous time systems, it has to be adapted to the discrete time/digital system utilized for control of the CO₂ laser. The adaptation to discrete time is defined in equation (2).

$$2. \quad C_n = C_{n-1} + K_p E_n + K_i (E_n - 1/2) t_d + K_p (E_n - E_{n-1}) / t_d$$

where

Cn current control output
 Cn-1 previous control output
 En error on current scan
 En-1 error on previous scan
 td time between scans

By using equation (2), an algorithm can now be constructed for control of the CO₂ laser. This algorithm has been built around equations (3) to (7) and is illustrated in figure C4.

$$3. \quad LCC = (SETP + (CORRECTION \times PROPORTIONAL_GAIN) + (INT_COR \times INTEGRAL_GAIN) + (RATE_COR \times RATE) (Hardware\ Coefficient / Max_PWR))$$

where

LCC	Laser control output
SETP	Laser control output in previous scan
PROPORTIONAL_GAIN	User entered proportional gain
INTEGRAL_GAIN	User entered integral gain
RATE	User entered gain
MAX_PWR	Maximum available laser output power
PWM_SCHEME_HARDWARE_COEFFICIENT	999

(Since output pulse width of 0 from pulse generation card gives laser output power of 0.0 W, output pulse width of 999 from pulse generation card gives maximum laser output power voltage scheme.)

HARDWARE_COEFFICIENT	1200
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Since D/A card output voltage of 0.0 V gives laser output power of 0.0 W, D/A card output voltage of 1.47 V gives maximum laser output power (D/A card output voltage of 1.47 requires that a D/A count of 1200 be supplied where D/A count = $(1.47 \text{ V}/5.00) \times 4095$).

$$4. \text{ CORRECTION} = \text{SETPOINT} - \text{LASER-OUT-POWER}$$

where

SETPOINT	user entered laser setpoint
LASER-OUT-POWER	measured laser output power

$$5. \text{ INT-COR} = (\text{CORRECTION} + \text{LAST-CORRECTION})/2 * \text{SCAN-RATE}$$

where

LAST CORRECTION	correction on previous scan
SCAN RATE	time between scans

$$6. \text{ RATE-COR} = (\text{CORRECTION} - \text{LAST_CORRECTION})/\text{SCAN-RATE}$$

REFERENCE

1. Pline, A.D. et al.: Hardware Development for the Surface Tension Driven Convection Experiment Aboard the USML-1 Spacelab Mission. AIAA Paper 89-0406, Jan. 1989 (also NASA TM-101404).

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